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SUMMARY TECHNICAL REPORT

OF THE

NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 15, NDRC

VOLUME 1

RADIO COUNTERMEASURES

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VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 15
C. G. SUITS, CHIEF

WASHINGTON, D. C., 1946



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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee



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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

To the able men of Division 15, who worked under the direction of Dr. C. G. Suits, and to the personnel of the Division's contractors belongs credit for the perfection of radio countermeasure devices and techniques which saved many American lives. Working in close cooperation with the armed services, the Division carried out a program of research which led to the formulation of a fundamental doctrine of radio countermeasures. The RCM activities included the development and use of search-ether receiving equipment, jamming systems, confusion and deception devices, and antijamming techniques. RCM was used successfully in aerial operations covering the Normandy landings, and during the latter stages of the war RCM rendered German radar systems practically useless.

The Summary Technical Report of the Division, prepared under the direction of the Division Chief and authorized by him for publication, describes the Division's program and the devices and procedures which were developed. We join with a grateful Nation in expressing our sincere appreciation to the men of the Division whose work contributed so importantly to the victory.

VANNEVAR BUSH, Director
Office of Scientific Research and Development

J. B. CONANT, Chairman
National Defense Research Committee

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FOREWORD

THE SUMMARY TECHNICAL REPORT of Division 15 is a compilation of technical contributions by the scientists and engineers of the contractors of Division 15, NDRC. The Division 15 wartime activity, called, for reasons of security, "Radio Coordination," consisted of the development of electronics countermeasures. Such countermeasures, for example, included the jamming and confusion techniques and equipments for use against radar and radio communications. Later in the war, countermeasures for newer types of electronics weapons, such as guided missiles, were developed. The whole field of activity included a great variety of radio and electronics specialties, unified in the common objective of denying to the enemy the use of his electronics equipments and weapons.

Electronics countermeasures, generally referred to as RCM, started in World War II with the passage of the *Gneisenau* and *Scharnhorst* through the English Channel. This operation was screened from British radar by electronic jammers installed by the Germans along the Channel coast. The success of the operation stimulated the development of RCM in Britain and later in the United States.

A small group was set up, under Dr. F. E. Terman, in the Radiation Laboratory at the Massachusetts Institute of Technology under Division D of NDRC, shortly after our entry into the war. This group later moved to Harvard University and became the nucleus of the Radio Research Laboratory. Division 15 was formed about this time, with responsibility for the broad field of electronics countermeasures, and the whole effort grew to one of the large technical projects of the war. It was a fascinating job and all the people associated with it felt they were contributing to victory.

The excitement of the changing technical needs in the field contributed to the success of the work, and remarkable teamwork was achieved on a team whose signals were constantly being changed by the enemy. The countermeasures team depended greatly upon its members in the Army and Navy and Air Forces for the success of the civilian effort.

Our allies, the British, made many important contributions to the success of RCM in World War II, particularly when the work was first getting under way in this country. Setting up the countermeasures group known as the American-British Laboratory Division 15, although intended primarily to serve the United States Eighth Air Force, did, to some slight extent, repay the British for their earlier help in this work.

Division 15 had many contractors in universities and in industry, and their combined efforts comprised the Division program. In the course of time, specialties developed, so that we gradually looked to Radio Research Laboratory, the largest of our laboratories, for the development of radar countermeasures; to the Airborne Instruments Laboratory, operated by Columbia University, for guided missiles countermeasures, and some additional still secret developments; industrial laboratories, particularly those of the Bell Telephone Company, Radio Corporation of America and Federal Telephone and Radio Corporation, took the chief responsibility for radio communications countermeasures; the special electronics tubes required for jamming purposes were developed in the laboratories of the Westinghouse Electric Corporation, Federal Telephone and Radio Corporation, and General Electric; Ohio State University specialized in antenna measurements; and the firm of Jansky and Bailey studied the vulnerability of the United States radio to jamming by the enemy.

One of the values that justifies a compilation of this kind is the technical lesson that may be learned for future guidance. One of the lessons of World War II is the necessity of giving some thought in time of peace to the problems of the national defense. It seems appropriate, therefore, at this point to draw attention to those technical problems which should be studied in the postwar period with future electronics countermeasures in mind.

Although there are necessarily a great many detailed items in a wartime research and development program in the radio countermeasures field, it is believed that a continuing countermeasures program in peacetime, under the sponsorship of civilian and government agencies, should consist only of the four broad categories described below.

It is probable that in the future, the ether will be filled with radio signals from a great many instruments of warfare such as radar, communications, guided missiles, proximity fuzes, and yet-to-be-developed controlled devices. The location, measurement, and analysis of these signals will be a vital activity in the future. It is believed, therefore, that a search ether program is one which must be a

continuing activity beyond the war just ended. To this end a long-range continuing search project should be established. It has been urged by Division 15 that such a program be established by the Services. It is felt that this is the most important portion of the radio countermeasures activity and it should also be supported by a civilian research agency.

Emphasis is placed on the *research* aspect of such an undertaking, since it is evident that new techniques must be developed and proved. The application of known conventional techniques would not be sufficiently effective to meet the need for searching the ether in another war; they were in fact only marginally adequate in the past war. The Radio Research Laboratory completed the development of an improved line of radar search receivers consistent with the OSRD philosophy concerning preservation of values, and the Airborne Instruments Laboratory completed what is considered to be a reasonably good search receiver for PF signals up to 275 mc. These represent a rather high degree of perfection of presently known receiver design techniques. The program referred to in this volume is the perfection of systems of searching, requiring a pure research approach in order to *develop new techniques* which will really meet the needs.

This art must be so developed that it will be possible to monitor continuously the entire radio-frequency spectrum, providing a suitable visual display showing any signals present as well as arrangements for recording such signals as may be received. The position of the signals in the spectrum should be accurately indicated, and means should be provided for identifying the character of any given signal (nature of modulation) and the direction from whence it is received. Provision should also be made for use of supplemental analyzer gear to determine in more detail the characteristics of the particular signal. There should be no spurious responses which could lead to false conclusions by the operator, neither should there be radiation from the receiver such as to interfere with other channels or to permit detection by an enemy.

It is considered essential to future security that research and development on devices for generation of high-frequency energy, which could be used for electronics countermeasures purposes, go forward actively. Since one does not know where in the spectrum the various enemy signals will appear, it is necessary that there be developed and made available sources of radio-frequency energy which, with suitable modulation, can be brought to bear on the enemy's transmissions, wherever they may lie in the radio-frequency spectrum.

It is believed that to a great extent commercial interests will provide the necessary impetus in this field, and that accordingly the postwar civilian research agency should adopt a countermeasures tube policy of carefully following commercial tube developments in the light of potential RCM applications. The trend of commercial developments may be expected to be toward higher frequencies and higher power levels, which would coincide with the RCM interest. There may, however, be gaps in the spectrum which will be left unfilled by commercial initiative alone, and it is suggested that the civilian research agency undertake to insure the filling of these gaps. It is hoped that this might be accomplished by interesting a commercial organization in undertaking the work as a part of its own development program; in some instances, however, a sponsoring contract might be required. Also, the development of modulation techniques should be followed closely, to insure that RCM needs can be met.

Another aspect of tube development that should be encouraged is that of broad tuning range. The restricted tuning range of magnetrons and velocity modulated tubes at the present state of the art entails vastly greater quantities of tubes and equipments for policing the spectrum than would be needed if really wide tuning ranges were available. If commercial interests do not vigorously promote research directed toward broader tuning ranges, it is believed that the civilian research agency should do so.

The foregoing remarks relate principally to tubes for transmitting and receiving purposes. However, in relation to receiver type tubes it should be pointed out that tubes suitable for use in signal generators, broadly tunable and adequate in power output, likewise are needed and should be followed closely.

It is believed that the development of non-reflecting surfaces will also have an important bearing upon any future armed conflict. It is expected that surface treatment of this sort will be essential not only in order to offset the usefulness of the enemy's radar, but also to deny him the effective use of other weapons, such as proximity fuzes, whose operation depends upon the reflection of electro-

magnetic waves. Emphasis should be placed on the broad band aspect of such surfaces, as the use of a great variety of frequencies by the enemy is a foregone conclusion.

An important part of the RCM research and development program during World War II was the studying and evaluating of countermeasures techniques, in order to realize the greatest effectiveness from our countermeasures effort in combat. It is important that some continued studies of this sort go on during peacetime, taking into account the new electronic devices as they are developed, as well as any new means available for countering such devices. This would of course include consideration of spot or barrage jamming as well as various deception devices, which would in turn be governed to some extent by the sources of jamming power available, the refinement of broad band amplifier techniques, etc. It also should include full consideration of the use of non-reflecting surfaces as another means of nullifying the effectiveness of enemy weapons which depend upon the reflection of radio waves.

Studies of the sort just mentioned should not be confused with the provision of an adequate countermeasure for any new device utilizing electromagnetic radiation. The importance of being able to counter any of our new electronic weapons which might be turned against us is well recognized, and it is believed that the Army and Navy laboratories are in the best position to provide such specific RCM devices for new weapons. It is hoped that the Services also will continue direct sponsorship of studies and evaluations mentioned above, but in any case it seems likely that the postwar civilian research agency will find it desirable to sponsor some continuing effort of this sort.

It is never easy for scientists and engineers to write reports of their work long after the interesting technical job has been completed. This is particularly true in the preparation of reports of wartime jobs. In Division 15, for example, reports were prepared in many cases as laboratories were terminating their work and as former employees were undertaking their postwar jobs. For these reasons great credit is due to the group of people who gave so generously of their time, in many cases long after their employment by NDRC or an NDRC contractor, to complete this vital record of one of America's wartime technical accomplishments.

Howard A. Chinn, as Editor-in-Chief, has performed a very great service in taking the responsibility for the technical content and arrangement of the material. He was ably assisted by those who are mentioned in the following Preface. The contributions of this group, both in line of duty and beyond the line of duty, made possible the compilation of this work.

C. G. SUITS
Chief, Division 15

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PREFACE

THE ACTIVITIES of NDRC Division 15 were primarily in the radio countermeasures field. In presenting the results of this work, this report is divided into four broad categories. These are (1) introduction, (2) technical developments, (3) nonradar applications, and (4) radar applications.

The Introduction, which comprises the first chapter of this report, provides orientation in the relatively new field of radio countermeasures. Although radio was used in World War I (primarily for communication), no extensive countermeasures activities were practiced. In World War II, on the other hand, with radio techniques being used for an almost endless variety of applications, radio countermeasures assumed an exceedingly important and, in some cases, a decisive role. As with many of the other electronic applications, the success with which this new tool was employed was often a function of the ingenuity of the person responsible for its application.

The fundamental technical developments which resulted from the work of Division 15 are described in five chapters, each covering a particular division of the work. A great many of the technical accomplishments, although originally undertaken with a view to their application to radio countermeasures, are of considerable value and interest to the electronics field in general. Because of the great diversity of requirements in the countermeasures field, there was an attendant development of a wide variety of techniques and equipment. These technical developments will probably find greater postwar application than in the case of many other wartime electronic devices.

The application of radio countermeasures techniques can be divided into (1) those for radar equipment and (2) all others. This division had no special significance. For convenience in nomenclature the latter category is termed nonradar applications.

In this report, the application of countermeasures to nonradar fields is covered in three chapters. A fourth, covering proximity fuze countermeasures has been omitted in view of the current security regulations.

All told, six chapters are devoted to the application of countermeasures to radar systems. Four of these chapters deal with equipment developments, while two of them cover the use of countermeasures in the various theaters of operation of the Armed Forces.

It is not possible within the scope of a report of this type to cover every development or to include all details of those developments that are mentioned. For this reason, a bibliography of the technical reports written by Division 15 laboratories is also presented. Of even more value is a digest of the contents of these reports. Report titles do not always convey an adequate description of the contents of the report. Therefore, the abstract of Division 15 Technical Reports, which is a part of this material, will prove very useful for deciding whether a given report contains material worthy of further review.

The main burden of compiling the Division 15 Summary Technical Report fell upon Roland B. Holt without whose able work the material could never have been adequately completed. James Wilson also assisted in compiling the material, and John N. Dyer acted as editor for Chapters 14 and 15 covering radio countermeasures in the various theaters of operation.

Frederick P. Cowan, David Middleton, Peter J. Sutro, and Donald W. Taylor contributed material contained in the Technique Development portion of this report. The last two chapters on applications in the theaters are a composite of information compiled by Robert B. Barner, John S. Foster, Jr., Stanley F. Kaisel, James M. Moran, Joseph M. Petit, Eugene Fubini, Charles W. Oliphant, Robert D. Sard, Don R. Scheneck, and J. Gregg Stephenson.

The abstract of technical reports issued by the Division was wholly the work of Arthur H. Halloran.

This opportunity is taken to thank all those mentioned above and also the many un-named assistants whose efforts contributed so much to the preparation of this report.

HOWARD A. CHINN
Editor-in-Chief

CONTENTS

CHAPTER		PAGE
	Summary	1
	PART I	
	INTRODUCTION	
1	Introduction to Radio Countermeasures	9
	PART II	
	TECHNIQUE DEVELOPMENT	
2	Noise Sources and Transformers	19
3	Electron Tube Development	39
4	Antennas and Radio-Frequency Power Transmission	54
5	Test Methods, Test Equipment, and Radio Countermeasures Training	66
6	Theoretical Studies and Miscellaneous Developments	80
	PART III	
	NONRADAR APPLICATIONS	
7	Nonradar Receiving and Direction-Finding Techniques and Equipment	149
8	Nonradar Jamming Transmitter Techniques	160
9	Nonradar Antijamming Techniques	188
	PART IV	
	RADAR APPLICATIONS	
10	Receiving and Direction-Finding Equipment for Radar Countermeasures	203
11	Radar Jamming Transmitters	214
12	Radar Deception and Confusion	230
13	Radar Antijamming Studies and Training	249
14	RCM in the European and Mediterranean Theaters	264
15	RCM in the Pacific Theaters of Operations	311
	Appendix	369
	Glossary	463
	Bibliography	467
	OSRD Appointees	497
	Contract Numbers	498
	Service Project Numbers	501
	Index	521

SUMMARY

THE WORK OF Division 15 in the field of radio countermeasures [RCM] had a very broad scope; it included fundamental research and development work on equipments for RCM, consultant services to manufacturers of these equipments, theoretical studies and other activities which led to the formulation, in close cooperation with the Armed Services, of a fundamental doctrine of the radio countermeasures science, and even included extensive participation by its civilian scientists in the planning, execution, and analysis of countermeasures operations.

The promulgation of the basic principles on which RCM operations were based, fortunately, was practically completed early in World War II. Briefly, RCM activities include the development and use of receiving equipment, jamming systems, confusion and deception devices, and antijamming [AJ] techniques. This broad division of the field holds equally well for radar, communications, guided missiles, proximity fuzes, and other types of countermeasures. The problem generally repeats a familiar pattern: viz., the operating characteristics, location, and tactical use of the enemy equipment must be ascertained; the proper tactical and technical combination of jamming transmissions and/or confusion and deception techniques for rendering this equipment as nearly useless as possible must be employed; and finally, our own devices of a similar type must be protected against the enemy's countermeasures activity.

The extremely diverse nature of the frequency ranges, power output, type of signal employed, antenna directivity, and other features of enemy electronic equipment demands that a similarly diverse collection of RCM equipment be available. A complete countermeasures program, therefore, calls for the development of search receivers in all frequency ranges capable of handling all types of signals, transmitters of all power levels, frequency ranges, types of output signals, and other features, a very wide diversity of deception and confusion techniques and equipment, and as many AJ techniques as possible. Compromises have had to be made in the design of many RCM equipments, so that a given unit could be used in several ways, to prevent the necessity of developing an almost astronomical number of separate equipments. Since it was not feasible to manufacture in large quantities all the sets developed, it was necessary to make available, on the basis of probable need, large quantities of certain equipments, and to hold in reserve finished designs of other equipments for possible contingencies. For this reason, the Division 15 developmental program included the development of as many diverse equipments as time allowed; thousands of units of some types were manufactured, while some were never carried past the prototype stage. Although only a few of the developments described in this report received widespread operational application, the others were of inestimable value as insurance.

The radio countermeasures activities of Division 15 were roughly divided between radar and nonradar countermeasures activities. Certain developments and techniques were common to both fields; these are discussed in the first main division of this report. Such activities include studies of modulation sources for RCM transmitters; electron tube developments; development of antennas and transmission lines; and development of test methods, equipment, and RCM training techniques. Many of the theoretical investigations carried on by the division were also applicable to both radar and nonradar countermeasures.

It was recognized early in the RCM program that the most useful type of jamming signal was noise. Other specialized types of modulation were applicable in special cases, but well over 90 per cent of the transmitters built for RCM use were noise-modulated. This meant that an extensive program for the investigation of noise sources and associated problems was necessary. Most of the work was centered on perfection of devices for the use of photoelectric and gaseous-discharge noise phenomena, although certain other miscellaneous types of noise production were investigated. In connection with the developments of the noise sources per se, it was necessary to build amplifiers which would correct the faulty spectral distribution of the noise produced, and also to build transformers which would make the output of noise sources directly applicable to the modulation of transmitters. Such developmental work naturally included a

considerable amount of fundamental research on the phenomena responsible for the production of noise, on the modification of these phenomena by imposed conditions (such as magnetic fields), on the development of methods for measuring noise, and on the fundamental electrical properties and materials used in the construction of noise-handling transformers.

The RCM program required the development of a large variety of vacuum tubes. This is easily understood in view of the fact that it was necessary to cover, at various power levels, large portions of the spectrum which were virtually unexplored at the beginning of World War II. It was necessary that this coverage be made by tubes having suitable ease of tuning, modulation properties, and operating stability. The electron tube developmental program sponsored by Division 15 resulted not only in the production of several dozen types of tubes, but also contributed in a fundamental way to the basic theory of tube design and to several related fields of endeavor. Tubes suitable for local oscillator applications in the frequency range 3,000 to 11,500 mc were reduced to practice. Parallel-plane triodes, suitable for use as amplifiers and oscillators for frequencies as high as 3,000 mc, were developed. A series of low- and medium-power magnetrons, including split-anode and "squirrel-cage" types, were developed in the frequency ranges from about 90 mc to well over 3,000 mc. Higher-power magnetrons for use in the high-frequency range were developed which were capable of delivering as much as 10-kw output. A new type of tube, the resnatron, was developed which was capable of power outputs of the order of 50 kw at 500 mc. Many of these tube developments will undoubtedly have a profound effect upon future electronic research and development, especially in view of the fact that the tube program represented an effort to cover as much of the frequency spectrum as was feasible, at all power levels, with tubes capable of being tuned over large ranges.

A further extremely important consequence of the tube development program was the careful study, much of it in the nature of basic research, of the fundamental principles of operation of some of the tubes produced. The work with magnetrons, velocity-modulated tubes, and resnatrons is especially noteworthy in this connection. In a similar way, research done on coaxial and open-wire line oscillator circuits and resonant cavity circuits for use with these tubes is of great importance in the field of basic electronics.

The antenna and r-f power transmission research and development carried on by Division 15 was necessary because antennas suitable for RCM applications having the required frequency range, directivity patterns, and physical configurations, were not available. The most remarkable single feature of the antennas developed in this program was the extended band coverage. Receiving antennas operating over frequency ranges of 3 to 1 were not uncommon, and transmitting antennas with very large bandwidths were developed. Although attention was given to antennas for ground-based, shipborne, and airborne use, the very nature of the countermeasures program dictated a wider use of airborne equipment than of any other types. Consequently, more attention was given to airborne antennas than to other kinds.

Dozens of antenna types were investigated, and a great number of these reached the production stage. As was the case with other RCM equipment, the number of antennas of a given type which were used, operationally depended very widely. Over 10,000 of one type of antenna described in this report were manufactured, and only 1 or 2 of several other types were used in actual operations. Here, again, the techniques developed, especially along the line of wide frequency coverage antennas for aircraft, are likely to prove of considerable value for future applications.

Among the features of some of the countermeasures antenna developed are their wide frequency coverage, their considerable variety in directional patterns, their polarization characteristics (including some which were circularly polarized), and their various mechanical features (such as low drag type antennas for high-speed aircraft). The frequency range covered in Division 15 investigations was from the broadcast range up to well above 10,000 mc. As mentioned above, it was necessary to employ several entirely new types of antennas to real-

ize the objectives of the program. Radio-frequency power transmission equipment, such as r-f switches, special transmission lines, and filters were also found to be necessary adjuncts to the RCM program and were therefore included as a part of the developmental effort.

Testing techniques, both for laboratory use and for field use, were found to be of the utmost importance in the radio countermeasures program. The extremely diverse nature of the RCM equipment developed demanded an even more diverse line of test equipment. This included special tube testers, noise analyzers, wattmeters, wavemeters, transmitter alignment indicators, heterodyne frequency meters, test oscillators, signal generators, crystal voltmeters, wide-band oscilloscopes, antenna measuring equipment, spectrum analyzers, equipment for receiver vulnerability testing, and many other types of specialized test equipment. Many of the devices employed for laboratory testing were packaged in a form suitable for field application, and moderate numbers were manufactured. Here, again, many of the techniques employed were of a fundamental nature and will influence electronic research and development for some time to come. Many of the methods and some of the equipment growing out of this program were found to be directly applicable to the training of Service personnel responsible for the operation and maintenance of test equipment.

The theoretical work done by Division 15 included basic studies on jamming signals, studies on the transmission and reflection of energy, and various miscellaneous investigations. The studies of jamming signals included basic noise studies, theoretical and basic experimental work on the visibility of radar signals through noise, and frequency-modulation investigations. These studies had a profound influence upon the design requirements finally adopted for the bandwidth, type of modulation, power output, etc., of jamming transmitters, and also on the AJ recommendations it became possible to make for the design of better radar, communications, and other electronic equipment.

The investigation of the transmission and reflection of energy had direct application to the design of transmission lines, wave guides, and antennas. It also had considerable influence on the development of confusion and deception electromagnetic wave reflectors (see below).

Miscellaneous topics investigated included theoretical studies of the method of operation of magnetrons, calculations of the probability of intercepting enemy signals of an intermittent character with a search receiver, an investigation of the use of models in design of antennas and in studying radar echoes, and various other topics. Although no essentially new mathematical techniques were employed, the solution of some of the problems required rather novel methods of attack, and the guiding influence on the overall RCM program of the theoretical work done cannot be overemphasized.

The nonradar applications of countermeasures equipment are discussed in the second main division of this report. These applications included development of receiving and direction-finding [DF] techniques and equipment, jamming transmitter techniques and equipment, AJ techniques, and special techniques for proximity fuze countermeasures.

It was found that, for most communications intercept work, commercially available receivers were adequate. Some work on the arrangement of a combination of such units in a suitable way (especially on aircraft) was found necessary to provide a complete search and monitoring service. The noncommunications portion of this activity, however, required special equipment.

A considerable amount of work was done on countermeasures and anti-countermeasures for radio-navigation aids, on the development of radio direction finders and their countermeasures for the frequency range 1.5 to 100 mc, on methods for deception of enemy DF equipment, and on electronic tuning for panoramic reception. Many of the techniques investigated are of permanent value. Specific equipment developments in this field included a panoramic receiver for guided missile and other intermittent signal search, and a special recording receiver designed to be incorporated in a signal-repeating jamming system.

Application of jamming transmitters to the nonradar countermeasures problem involved a considerable amount of preliminary study. For

example, in jamming guided missiles and similar devices, noise is not always the most advantageous type of modulation; consequently, a study of the effectiveness of various types of jamming signals had to be undertaken. Here, too, the relative advantages of barrage jamming (jamming over a wide frequency range) versus spot jamming (jamming only the victim-signal frequency) had to be weighed carefully before designing equipment to do a particular jamming job. Actual equipments developed for this type of application included airborne, parachute-borne, ship-borne, and ground-based units with power outputs varying from a few watts to several kilowatts.

A considerable number of our own electronic devices were studied in order that specific suggestions could be made as to design of equipment or modifications for existing equipment to minimize the effects of enemy jamming. A necessary preliminary to this investigation, of course, was a study of the fundamental properties of various types of jamming and of the vulnerability of various types of electronic equipment to jamming. Special test equipment was developed for some of these studies. A large number of communications systems, including voice, radiotelegraph, radioteleprinter, pulse communication systems, etc., were studied and definite recommendations as to improvement made. Several types of guided missile receivers, radio altimeters, and other similar devices were also studied.

Because of the special nature of the problems involved and the high degree of security necessary, the work done on proximity fuzes was a more or less separate part of the RCM program. General studies were made, both theoretically and experimentally, of proximity fuzes and of possible countermeasures to them. The measures considered included the use of confusion reflectors (Window) as well as of electronic jamming. Various types of jamming modulation were considered, and two jamming transmitters were developed to the production stage during World War II, as insurance in case the need for them arose suddenly. A special search receiver for detecting proximity fuze signals was also developed. Since the enemy employed no proximity fuzes during the war, proximity fuze countermeasures operations were limited to search activities.

The third principal section of the report is devoted to applications to radar countermeasures, which, because of the tactical situation, proved to be the most useful part of the program in World War II. Here, again, the program involved development of receiving and direction-finding techniques and equipment, jamming transmitters and systems, deception and confusion techniques, and antijamming methods.

Receiving equipment developed for countermeasures use included a complete line of search receivers in the frequency range 40 to 11,500 mc. The development of such receivers made necessary a considerable amount of work on the fundamental properties of r-f filters, mixers, local oscillators, amplifiers, presentation circuits, and other fundamental circuits required by these receivers. Many of the techniques developed as the result of these studies should prove useful for a long time to come in wide-band receiver design.

In addition to such search and analysis receiving equipment, receivers for warning that a target was being observed by enemy radar, receivers for setting jamming transmitters on enemy radar frequencies, and receivers employing other special design features (such as very rapid sweep, etc.) were also designed. The Armed Services procured several thousand receivers based on fundamental Division 15 designs.

Radar jamming transmitter developments included a wide variety of equipments, with power outputs from a few watts to many kilowatts, frequency coverages from about 20 mc to several thousand mc, and a considerable range of other features. These transmitters ranged in size from the small low-power transmitters which, before the end of World War II, flew in every heavy bomber in the European Theater of Operations [ETO] to the giant ship-borne Elephant jamming system and the ground-based Tuba jammer, both of which were able to put out tons of kilowatts of power.

The jammers varied widely in complexity: a simple barrage jammer which was adjusted before an operation and merely turned on and

off as occasion demanded; a completely automatically operating jamming system capable of searching out and jamming enemy transmissions by itself; a jamming system employing several operators at once and capable of determining the frequency, pulse length, pulse-repetition frequency, direction, frequency stability, and many other features of an enemy signal. Here, as in many other parts of the Division's work, the techniques perfected during the development of specific equipments are of fundamental and lasting value.

Closely related to the use of jamming transmitters is the use of radar deception and confusion devices. The more widely used devices in this category have been mechanical reflectors, although electronic deception and confusion devices are also available. The mechanical reflectors are, essentially, metal foil cut in various sizes and shapes. They include narrow strips a half wavelength long, very long strips, corner reflectors, and many other miscellaneous types. Many tons of such metal foil deception and confusion devices were employed during World War II.

A great deal of theoretical and experimental work was done to determine the optimum size and shape for such reflectors. It was also necessary to conduct many experiments and a considerable amount of theoretical investigation to determine the optimum tactics of the use of such reflectors. The combined use of this countermeasure and electronic jamming, which was carried out on a large scale in the ETO, rendered the enemy's radar system practically useless during the closing phases of World War II. In addition to the mechanical deception and confusion devices, various electronic means of disguising either the direction, range, or apparent size of a radar target are available and have been used operationally with success.

Protection of our own radar sets against jamming activity of the enemy was also a part of Division 15 activity. A number of laboratory studies concerned with the development and application of good basic AJ design for radars were carried out. Investigations were made of many specific radar equipments, and the engineering of retroactive AJ modifications for radars already in the field was carried through for several systems.

Radar AJ, more than almost any other part of the countermeasures program, depends for its effectiveness upon operator training. Consequently, a part of the program of the division was devoted to the development of training apparatus and the training of instructors in AJ techniques for the Armed Services.

The participation of the division in operational phases of World War II furnished a great deal of information which was of value to the division in the design of RCM equipment. At the same time, it aided the Armed Services by providing RCM equipment experts in the field. Division 15 personnel participated as early in World War II as the first operations in the Aleutians and in the invasion of Sicily.

A branch laboratory with a staff of about 80 people was maintained for over a year in England by Division 15. There were also Division 15 representatives in the Mediterranean Theater, in France immediately after the invasion, and in the investigating groups that went into Germany after the surrender. Division 15 representatives also, at one time or another, visited every important center of countermeasures activity in the Pacific Theater. The effectiveness of such civilian aid was enhanced by a system of rotation, whereby men with the latest laboratory techniques were frequently sent to replace those with theater experience, who in turn helped formulate the future research policy of the Division.

Analysis of the results obtained from the operational use by the Armed Services of RCM equipment leaves no doubt as to the soundness of the "investment." The entire cost of the program was paid for over and over again by the saving in aircraft alone (not to mention the number of priceless lives also saved) resulting from successful application of the equipment and techniques developed by Division 15.

SECRET

PART I

INTRODUCTION

Chapter 1

INTRODUCTION TO RADIO COUNTERMEASURES

1.1 INTRODUCTION

THE NEUTRALIZATION of the effectiveness of enemy radio communication, radar, and controlled-device systems by electronic or other means is known as radio countermeasures [RCM]. RCM also includes the problem of radio intercept [RI] but, since this is predominantly a tactical problem, it is not treated in this book, which is concerned mainly with technical matters.

Application of RCM requires careful preparation. The degree of success will usually depend upon the craftiness of those planning the operation, the speed of its application, and the skill of its execution. The importance of planning, speed, and execution becomes obvious when it is remembered that the enemy is "calling the tune." Whether communications, radar, or radio-controlled devices are used, the enemy selects the frequencies, the output power, the location and amount of the equipment, and the operating procedures. The effectiveness of the enemy's activities will therefore depend upon our nimbleness in making use of available means to nullify these activities. By the same token, the enemy's continued success depends upon the speed with which he can shift frequencies, locations, etc., and start the cycle over again. The application of RCM can thus be described as a continual scramble or series of "emergencies."

Since it was not feasible in World War II to equip every theater with jamming transmitters and other countermeasures devices for use against every possible type of radio equipment, those on the spot had to make effective use of equipment on hand whenever the enemy turned up at unexpected places in the frequency spectrum. As this point cannot be overemphasized, an attempt has been made here not only to include a description of the actual equipments which have been used for RCM purposes and of the actual techniques employed but also to set forth some of the fundamental philosophy that is essential to the successful use of these devices.

1.2 TYPES OF COUNTERMEASURES

Basically, the methods employed for communications, radar, and controlled-devices countermeasures include straightforward jamming and the use of deception and confusion devices. Jamming may be considered a "brute force" method of accomplishing the desired result, whereas confusion and deception devices may be thought of as a more subtle method of attack.

Closely allied to these direct RCM methods is the use of homing and direction-finding [DF] receivers and, in the case of radar, of warning devices to advise when one is being scrutinized by enemy radar systems. Furthermore, in both communications and radar, various antijamming [AJ] techniques may be applied. Finally, since the successful application of RCM implies an accurate knowledge of the disposition, operating characteristics, and habits of the enemy systems, it is essential that adequate search equipment also be available as part of the complete RCM program. Search equipment, or suitable modifications of search equipment, must also often be used for monitoring the enemy transmissions during the application of direct RCM procedures. Thus, RCM facilities include

1. Receivers (search, monitoring, warning, and homing or direction-finding types).
2. Jamming transmitters.
3. Confusion and deception devices.
4. Antijamming techniques.

Since the method of practicing RCM in the communications field is often different from that which is appropriate in the radar field (or in allied applications, such as radio-controlled devices), it is important to differentiate between the two fields. This is done in the following discussion and it is essential that this definite distinction always be kept in mind.

1.2.1 Receivers

SEARCH RECEIVERS

Before the use of jamming transmitters or confusion and deception devices can be planned

in detail, accurate information must be available concerning enemy communications, radar equipment, and radio-control systems. In the preliminary stages of the planning it may be sufficient to make use of such generalized information as may be available concerning the probable numbers of enemy equipments, their disposition, and the frequency band in which they operate. For a specific application, however, it is essential to know the exact frequencies employed by the systems to be neutralized, their methods of operation, what reserve facilities are available to the enemy, and the geographical locations of the systems involved. Such details are required because, in general, the jamming or deceptive means to be used must be accurately adjusted for the frequencies involved and operated only when they are likely to be effective and in such a manner as to neutralize all enemy facilities (or at least as many as possible), whether they are regular or emergency systems.

The equipment used for searching, analyzing, and direction-finding on enemy communications channels is, for the most part, conventional in design and has been catalogued elsewhere.[a] For this reason, the only communications search equipment covered in this book is that which was developed for special purposes by the laboratories operating under the auspices of NDRC Division 15. Equipment operating at radar frequencies, however, is relatively new and is therefore covered in detail.

A properly equipped searching expedition, in addition to being used to determine the radio frequencies employed, can ascertain many other operating characteristics of the enemy equipment. A knowledge of these characteristics will not only considerably facilitate neutralization of the equipment but will also provide information that may be valuable from an intelligence standpoint. In lieu of the actual capture of an enemy system, such data permit an informed estimate to be made of the capabilities of the equipment.

Radar search can generally be most readily accomplished by observations made from aircraft, since the emissions from such systems seldom extend appreciably beyond the radio "line of sight." Thus, unless the terrain is particularly favorable, only those radar equipments which are immediately adjacent to the fighting front will be observable by ground-based radar search receivers. This was true in the European Theater of Operations [ETO] between the British Isles and the Continent. In the Alaskan Theater, the terrain was such that observations of the enemy radar equipment on Kiska could be made from Amchitka. Thus, although airborne searching may be more common, the desirability of being prepared to undertake such operations with mobile, portable, or ground-based equipment must be borne in mind. The search receivers described herein are primarily intended for airborne applications but can be adapted to these other types of service.

In connection with airborne search, it should be noted that radar emissions can be received at distances from the radar that are considerably beyond the maximum detection range of the radar system. Under these circumstances it is often possible to observe the operating characteristics of an enemy radar system without coming within its field of view.

Receivers for determining the characteristics of the control signals used for enemy radio-controlled devices (e.g., radio-controlled tanks, glide bombs, or rockets) present a particularly difficult search problem. This arises from the fact that the signals are observable only for the few seconds (perhaps a minute, at the very most) in an actual attack during which the vehicle is making the target run. Even within this short period of time the control signals may not be continuously radiated, since they may of necessity be intermittent. Furthermore, the control signals may be confined to a very narrow channel, located almost anywhere in the radio spectrum. Finally, false or decoy signals, on frequencies far removed from those actually used, may be transmitted by the enemy during the attack.

Monitoring Receivers

Receivers for monitoring enemy transmissions or for "setting on" jamming transmitters are essential to many RCM operations. In the

[a] See the *Signal Communication Equipment Directory* prepared by Military Intelligence Branch, Office of the Chief Signal Officer.

first place, such equipment allows monitoring of the enemy transmission. This can provide a great deal of very useful information, especially if the enemy indicates the effectiveness of the RCM operation being attempted against him by attempting to change frequency, shutting off his equipment, turning off lobe switching (on radars), or otherwise changing his mode of operation. In the second place, use of such equipment for setting on a jammer will obviate the necessity for absolute determination of frequency, since the equipment can be arranged to receive both the signal and the jamming simultaneously and will allow following with the jamming transmitter any frequency shifts which the enemy may attempt to avoid the jamming.

Direction-Finding and Homing Receivers

Direction-finding means are also a part of the search program, since it is essential to ascertain the location of enemy installations. Because of the wide frequency range that is of interest, the various polarizations of the signal, and other factors, this is not a simple problem. Successful systems have been devised, nevertheless, and are described elsewhere in this volume.

Homing receivers are another important type of RCM equipment, since they may be instrumental in making it possible to undertake a most effective counter-countermeasure—finding and destroying enemy jammers. Besides being useful for homing on the source of enemy jamming transmissions, such receivers can also be used to home on friendly or enemy communications and radar systems.

Warning Receivers

Radar warning receivers, which are more or less automatic in operation, are useful for advising when one comes under observation by enemy radar. For example, an aircraft-interception [AI] warning system may be used to warn aircraft when attack by radar-equipped enemy fighters is imminent. A gun-laying [GL], searchlight-control [SLC], or ground-controlled-interception [GCI] warning receiver would advise when danger from these sources is likely. Experience has shown that the protection afforded by equipment of this kind is valuable for easing the inevitable tenseness that accompanies the possibility of attack without warning.

In addition to its application to aircraft, such equipment is also useful, of course, for warning surface vessels or submarines of exposure to various types of radar. The use of warning receivers requires, however, a thoroughly accurate and reliable tabulation of the characteristics and methods of use of the enemy installations.

1.2.2 Jamming Transmitters

Jamming transmitters are usually designed for use against a specific type (or types) of enemy system. They may be classified as airborne, portable, mobile, expendable, ship-borne, or ground-based, depending upon their intended method of use. Because of wave propagation considerations, a given short-distance communications or radar channel can, in general, be jammed with the minimum of power if the jammer is airborne. Airborne jammers are, however, faced with many limitations, such as limited primary power supply, problems of antenna installation (particularly at the lower communication frequencies), difficulty of maintaining a continuous jamming operation, dependence upon weather, and vulnerability to attack. For these reasons, the use of ground-based, mobile, or portable jamming equipment is indicated wherever practical.

The most important advantages of ground-based jamming transmitters are the relative ease of continuous operation (if required), the possibility of inconspicuous location, and the availability of greater amounts of primary power. Advantage may also be taken of available space to employ directive-antenna systems in order to send a large percentage of the available power toward the victim and away from any friendly systems that may be operating in the same general region of the frequency spectrum. Unfortunately, however, the distances involved, the nature of the surrounding terrain, and the amount of transmitter power that can be conveniently radiated do not permit the widespread practice of jamming from

SECRET

ground locations, particularly in the case of radar.

Expendable jammers are generally of the type that may be dropped close to the victim station by parachute or in a bomb casing. A desirable feature of this type of jammer is that it may be sowed in quantities near the victim, where it will operate until located and destroyed or until the power supply is depleted. Such jammers can be effective even though they have very low power. Expendable transmitters seem to offer more possibilities in the communications field than in radar, and, consequently, their development in the latter field has not been exploited to any extent.

Communications Jamming

Communications jamming transmitters, if properly used, can be very effective against ground force command nets, armored vehicle communication systems, walkie-talkie equipments, air-to-air and air-to-ground communications systems, and other relatively short-distance communications channels. Although it is possible, under favorable conditions, to attempt to jam long-distance point-to-point circuits, the success of such operations may be rendered unprofitable by the amount of power that may be needed, by the lack of suitable geographical locations for the jammer (which must blanket the terminal of the enemy channel with a frequency determined by the intended victim), by the large number of frequency channels that the enemy may have available for emergency use, and by the need for jamming all channels practically continuously if the "blockade" is to be effective.

In any event, the jamming of communications circuits of any kind must be coordinated with the activities of any intelligence services that may be using the channels to obtain information concerning enemy activities. The benefits to be gained by jamming must always be weighed against those to be obtained by monitoring the intended victim signal for information purposes.

Jamming of enemy ground-to-air communications channels may be a very effective means of neutralizing the effectiveness of enemy GCI radar systems. In fact, it is just as effective as jamming the radar itself since, if proper instructions cannot be transmitted to the interception fighter, the usefulness of the GCI system is destroyed. The jamming of such ground-to-air circuits may be most readily accomplished by airborne jammers in the vicinity of the victim stations. Where an alternative exists, however, this may not be the best method, since such airborne jammers may become the target of enemy action.

In favorable situations, high-powered, ground-based communications jamming equipment, using directive antennas, may be advantageously employed to send signals into the region where enemy GCI fighters are operating. This procedure will result in the jamming of only the ground-to-air link (and not the air-to-ground link). Since the ground-to-air link is the important link of the GCI system, however, its jamming should make GCI operations impossible or at least very difficult.

Aircraft-Interception Radar Jamming

If the enemy fighters are equipped with AI radar, it will be desirable to jam the AI system also. Again, this can be done most effectively with airborne jammers but they, in turn, may become the object of an attack guided by homing devices. In this case, also, if the distance and the terrain involved are favorable, use may be made of high-powered, ground-based jamming transmitters operating at the enemy AI frequencies.

Gun-Laying and Searchlight-Control Radar Jamming

In the jamming of GL and SLC radar (also of GCI radar, if the radar itself is to be jammed), the jamming equipment must be airborne, generally by the target aircraft, since the resolution of these radar equipments will probably be such as to discriminate reasonably well against interference from directions other than that in which the radars are oriented. In daytime tight-formation flying, all jammers coming within the beamwidth of the radar will contribute to the overall effect but, at the same time, all targets within a pulse length will contribute to the size of the radar echo.[b]

[b] For further explanation see discussion of operational tactics in Chapter 11.

Early-Warning Radar Jamming

Early-warning [EW] radar systems may be effectively jammed by airborne equipment or by ground-based transmitters where the geographical features of the situation are favorable. It is important to note that jamming operations must be carried out against all existing systems, regardless of their frequency, if the overall operation is to be successful. It has been found that in some theaters of operations, for example, the ETO, the need for EW jamming had to be carefully evaluated in view of the proximity of the fronts and the large concentration of other types of radar which, in such special situations, made possible the supplying of all the warning that is of practical value. Where EW radar is used to place GCI radar on the target, the jamming of the former (as well as of the latter) may be of some value.

In any radar jamming operation it is important not to use the jamming transmitter before entering the field of view of the intended victim radar. If the jammer is used too soon, the jammer-carrying craft will advertise its presence to the enemy by indicating the bearing (but not the range) from which the jammer is approaching.

Coastal-Watch Radar Jamming

Coastal-watch radar may be jammed from transmitters carried on shipboard or on low-flying aircraft or, when a suitable location is available, from ground-based jammers. As with all radar jamming, it is important to note that the radar will be subject to jamming only when it is pointed toward the source of jamming signals. The resolution of the radar receiving antenna determines the arc over which it is susceptible to interference. If jamming over a considerable arc is desired, it will be necessary to employ a number of jamming sites.

Radio-Controlled Devices and Proximity Fuze Jamming

For the most part, jamming (or other RCM operations) attempted against radio-controlled devices or proximity fuzes is highly specialized and depends very largely upon the characteristics of the equipment which is being countered. Transmitters, receivers, etc., developed for other purposes may be used in this work in many cases. Very little of a general nature may be said. Specific equipments and techniques for radio-controlled devices RCM are, however, discussed in Chapters 7 and 8, and specific equipments for proximity fuze RCM, in Chapter 10.

1.2.3 Confusion and Deception Devices

Communications Confusion and Deception Methods

The application of confusion and deception methods in communications channels does not, for the most part, require any special devices other than transmitting and receiving equipment operating on the proper frequencies. Such practices do require ingenuity on the part of the operator.

Radar Confusion Methods

The method which has been most used for confusing enemy radar is the "Window operation." A Window operation involves the sowing of radar echo-producing reflectors to the extent that an entire volume of space becomes infested and the multiplicity of echoes of false targets will conceal a true target in this volume.

The appearance of these false echoes is not very different from that of an aircraft except that their apparent speed, which depends upon the wind velocity, is very low. For complete protection the infestation must be sufficiently dense that the false echoes are strong enough to conceal the echo from an aircraft flying through the infested volume. Reflectors sown from the surface by means of rockets or suspended from a balloon or kite to simulate a surface target have been used, especially for naval applications.

Radar Deception Methods

Considerable attention was paid in the RCM program to methods of deceiving radar operators. The objective was to cause the enemy operator to make a false report, not knowing that the echo received by his equipment was not that of a legitimate target. A Window operation may be so carried out as to fall into this category, particularly in areas where Window

has been in regular use and the enemy radar operator is used to seeing it as cover for a normal raid. A few aircraft carrying sufficient Window may eject it at a high rate in a rendezvous area, if in view of enemy EW radar, in order to alert the enemy's defense system on days when no raid is planned. Another scheme, where there are several possible targets in one area, is to send a few special aircraft with sufficient Window as a diversionary raid. Then, if Window is dropped in the proper quantity by the main raid, there will be no way for the enemy radar operator to distinguish between the main raid and the diversion. Obviously, in using Window to deceive EW radars, the frequency coverage must include all radars which the enemy will use for this purpose.

Various electronic deception methods, involving transmission of false signals on the enemy radar frequency, also received attention. These are generally highly specialized and depend to a great extent on the exact characteristics of the enemy radar. Some discussion of such methods is given in Chapter 12.

1.2.4 Antijamming Methods

The use of jamming, confusion, and deception methods may be thought of as offensive countermeasures, whereas the development of AJ techniques may be considered defensive.

A number of AJ methods and devices have been developed for communications radar, and radio-controlled systems. In many instances, these are incorporated in the basic design of the equipment involved. This is true of communications receivers, since it has been the general practice for some time to include features that would assist in segregating the desired signal from any interfering signals. As new methods became available, it was possible and worth while to supply modification kits for application to some types of existing equipment in the field. The best of these devices are of little value, however, if not properly used.

In both communications and radar, *there is no substitute for experience in reading the desired signals through interference and for the will to do so*. The importance of this fact cannot be overemphasized. Experience in the field has demonstrated that untrained operators do not take full advantage of every means available to receive the desired signal. A still more serious fact is that, upon being exposed to novel forms of interference, untrained operators have even given up trying to operate their equipment or have taken it apart to find faults which were mistakenly thought to exist within the set. These tendencies can be overcome only by adequate training and frequent exercises during which the operator has an opportunity to familiarize himself with the various possible forms of interference that may be encountered and learns to carry on as well as possible in spite of the disturbances. The importance of this AJ method is evident when it is realized that by proper operator training it may be possible to force the enemy to use from two to ten times as much jamming power to achieve a desired effect. At the frequencies involved, this increase is sometimes difficult or even impossible to achieve.

Another potent AJ measure for both communications and radar is the making available of a number of alternate operating frequencies, together with means for rapidly changing from one to another. The range of available frequencies should, of course, be as wide as possible and the time necessary for making the shift should be as short as possible, preferably of negligible duration.

In some instances the incorporation of an AJ design feature will be possible only with an accompanying impairment in the performance of the equipment involved. In general, however, it is probably prudent to make some sacrifice in performance in order to combat jamming, since the finest system is entirely useless if it is successfully jammed.

A feature which generally improves the AJ properties of a system without impairing its performance is the use of high directivity or resolution. Systems having high directivity are more difficult to jam, as a rule, because of their discrimination against unwanted signals arriving from directions other than that in which they are oriented. Microwave sets lend themselves particularly well to improvements along these lines.

1.3 SUMMARY

The above discussion has dealt with the relation between the four basic parts (search, jamming, confusion and deception, and antijamming) of the RCM program. Part II of this volume deals with technique developments, theoretical studies, and test equipment and methods which were found necessary for the perfection of various RCM applications. Part III deals with nonradar applications, and Part IV with radar applications. This volume should be used in close conjunction with the monograph[809] of the Radio Research Laboratory on fundamental techniques used in the development of RCM equipment.

PART II

TECHNIQUE DEVELOPMENT

SECRET

Chapter 2

NOISE SOURCES AND TRANSFORMERS

2.1 INTRODUCTION

FROM THE BEGINNING of the radio countermeasures [RCM] program of Division 15, it was realized that noise was a good jamming signal for all purposes, and later experiments confirmed the belief that for many applications it was the best one. Investigations into possible noise sources were therefore begun very early in the program. In January 1943 a thorough study of noise sources was organized with the establishment of a separate group at Radio Research Laboratory [RRL], Harvard University, for this purpose.

A laboratory was built up with equipment for physical research in photoelectric, gaseous-discharge, and related noise phenomena. This included a small machine shop, and laboratory equipment for the construction, pumping, and baking of vacuum tubes. The program that was carried out consisted of investigations into noise sources of all types (including photoelectric tubes, gas-discharge tubes, mechanical sources, and others) and the development of noise generators, studies of basic processes in noise production, development of noise-measuring techniques and methods, and investigations into video transformers for noise voltages. The results of theoretical studies on many of these problems are discussed in Section 6.2.

The greater part of the research, especially that of a more fundamental type, was conducted at RRL (under contract OEMsr-411), but a good deal of development work, especially on specific tube types, was carried out chiefly by the Radio Corporation of America (under contract OEMsr-1060), the General Electric Company (under contract OEMsr-931), also by the Bell Telephone Laboratories, Inc. (under contracts OEMsr-778, 940, and 966), and the Ballantine Laboratories (under contract OEMsr-1176).

In October 1943, a conference was held at RRL of representatives of interested industrial and government laboratories (including most of those mentioned above) to discuss problems of noise generation. Reports were presented summarizing the noise research at the various laboratories,[808] and a procedure was instituted for the dissemination of complete noise information by the National Defense Research Committee [NDRC] among the Division 15 contractors concerned. It was pointed out that a satisfactory noise source would be one which was stable, which had a uniform frequency characteristic, and which could replace one or more video stages in existing noise amplifiers.

2.2 PHOTOELECTRIC NOISE SOURCES

One of the first noise sources used in production equipment was the photomultiplier tube. The RCA 931 tube was found to be particularly good for this purpose, and an investigation of its characteristics was initiated. The conclusions drawn from this study led to research into better types of photomultipliers, which in turn resulted in the development of the improved 931A tube. The 931 and later the 931A were widely used as noise sources throughout World War II.

2.2.1 Research on the 931 Photomultiplier

The use of the 931 photomultiplier tube as a noise source was first proposed in the spring of 1942.[496] This idea was based on the fact that the photoelectric current emitted by the cathode of a photocell has a variational component due to random emission—that is, a shot effect. The mean-square noise current at the cathode is

$$\overline{i^2} = 2e\Delta f I_k, \tag{1}$$

where e is the electronic charge, I_k is the direct current at the cathode, and Δf is the frequency bandwidth of the noise under consideration. This initial noise current is amplified by the successive stages of the multiplier to give the anode current. If the gain of the tube is M, the mean-square noise anode current is

$$\overline{I^2} = 2e\Delta f M^2 I_k = 2e\Delta f M I_B, \tag{2}$$

where I_B is the average value of the anode current. Thus, the noise current at the anode is proportional to the mean current at the anode and to the gain of the tube for a fixed bandwidth. For a fixed divider voltage, the anode current can be varied within limits by varying the illumination at the cathode, whereas the gain M is a characteristic of the individual tube. The high value of M made the tube a relatively high-level, compact noise generator. The 931 tube was the standard noise source for jamming purposes for a long time.

In an extensive study[553] of the noise characteristics, it was found that the value of M, measured under standard conditions of light and voltage[a] at the time of manufacture, was a reliable indication of the performance of the tube as a noise generator. Tubes having widely different values of M were tested in a number of jamming transmitters (RC-156, AN/APQ-2, RC-183, and AN/APT-1). It was found that tubes having an M of 75,000 or greater would operate those particular transmitters satisfactorily. After a series of conferences with RCA and Service representatives, a new set of joint Army-Navy specifications were drawn up giving the number 931A to tubes having gains of 75,000 or over. At this time from 15 to 20 per cent of the tubes manufactured fell below this level. A research and development program was initiated at RCA, primarily aimed at the improvement of the 931 type of tube.

Both theoretical[522] and experimental[553] studies of the 931 at RRL demonstrated the importance of using a high supply voltage, preferably 1,000 v, and a voltage divider for the dynodes having sufficient current capacity to prevent nonuniform distribution of voltage (see Section 6.2.3). The use of too small a voltage across the last stages results in excessive space charge, which reduces the noise output and also distorts the spectrum. Under optimum conditions the 931 noise spectrum is flat over a wide frequency range[553] (up to 500 mc). The most disturbing characteristics which were revealed were the erratic operating and aging effects. It was found that during the first 15 min of operating the noise output decreased by as much as 15 db. Further operation resulted in a relatively slower rate of decrease.[471] The tube generally recovered after a period of inoperation, but the output seldom returned to the original value. Thus, there is a short-time high rate of decay and a long-time aging effect involved in the use of this tube. It was found that the output could be restored to nearly its original level by readjusting the light after the first 15 min of operation. It was recommended that this be done with all transmitters before the final tests were made. The spectrum and noise output were found to be independent of temperature between —50 C and +80 C.

Another multiplier tube in the experimental stage, the Bell Telephone Laboratory D159076 photomultiplier, was also studied. The fewer dynodes resulted in a lower overall gain than in the 931, and the noise output was 25 db below the minimum level set for 931A tubes. Only one tube was available for test.

2.2.2 Development of the 931A Photomultiplier

The tube research program mentioned above resulted in the development of the improved RCA 931A photomultiplier, which replaced the 931 and was widely used in various countermeasure applications.

At the time the project was started, the gain of the 931 was distributed about a median value of 400,000, with a minimum acceptable value of 12,000. About a year later the median gain was at 2,000,000 with an occasional tube at 10,000,000. The life characteristics were also greatly improved.[299] When first announced, the 931A had a 3:1 minimum gain advantage over the 931. By 1945 the average product had been improved by a factor of 5 in gain or equivalent noise output. At the same time, the life of the average tube was increased by a factor of 3.

In the general investigation of multiplier design[298, 299] it was shown that minor improvements could be obtained by alteration of the mechanical structure affecting the electron optics. This accomplished a reduction in noise limiting space charge, but the change was not considered to yield improvement justifying delayed production. Similarly, longer life was

[a] Illumination of 0.001 l, and 100 v per stage.

shown to be obtained by substituting more rugged, but less sensitive, secondary emission surfaces in the last, current-carrying stages; again the improvement did not justify complications of production. If complete redesign had been practicable, it was shown, an increased number of secondary emission sources would have yielded an increased noise output with no increase in applied voltage.

A detailed study was made of the possibilities of regeneratively increasing noise in a special photomultiplier in which a grid had been introduced between the photocathode and the first dynode.[298] A large transconductance-to-current ratio of 10 v^{-1} was obtained in this construction when it was operated with light of long wavelength. The noise output of this grid-controlled photomultiplier had a peak in the spectrum which could be located at various frequencies. Regenerative gains in noise were demonstrated to be of the order of 10 db in bandwidths of 2 mc up to 5 mc, with unexplored possibilities to 30 mc. However, no use could be found for this tube for jamming purposes. For the present, the development of the photomultiplier is considered completed, particularly for wide-band application. If a new program on multiplier development were begun, it would be profitable to consider increasing the number of secondary surfaces. The field of gaseous discharge seems, however, to be the most promising generally for noise development.

2.3 GAS-DISCHARGE NOISE SOURCES

A major portion of the noise research was devoted to the study of the noise characteristics of gas-discharge tubes. This involved both fundamental research on the nature of the processes involved and practical studies of the best tubes and methods of using them.

2.3.1 Fundamental Research

The research on gas discharges disclosed several new processes.[730] It was confirmed that the strong, nonsinusoidal oscillations which are present in hot-cathode arc tubes are plasma oscillations. The l-f noise and such h-f noise as is present were attributed to fluctuations in position and in density of the space-charge regions near electrodes.

The great increase in h-f noise when a transverse magnetic field is used was shown to be produced primarily by a narrow region, very close to the cathode, in which the positive-ion space-charge density is high and the gradient of density is also high. Electrons emitted by the cathode are caused by the magnetic and electrostatic fields to move in curved paths which return them to the cathode, as in a magnetron at cutoff, if no collisions are made with gas atoms. Most of the ionization occurs in a narrow zone in which the electrons are moving parallel to the cathode. This region is believed to produce h-f noise components according to the equation for plasma-ion oscillation

$$f = 2\sqrt{n}, \tag{3}$$

where n is the ion density. Since the space-charge density has a high peak in this region, each segment would have an oscillation frequency and amplitude characteristic of its density. The peak-to-peak voltages developed are from 0.5 to 0.9 of the arc drop, which is, in turn, of the order of the least ionization potential of the gas.

When cathodes are improperly activated, atoms of barium may be sputtered off the surface of the cathode. These atoms have a much lower ionization potential than argon, so that electrons quite close to the cathode will have sufficient energy to ionize them. Thus, the ionization region will be spread over a considerable distance. This will reduce the value of the space-charge density and lower the h-f noise components. Proper activation of the cathode eliminates these impurities and restores the noise-level characteristics of the gas for the values of current and magnetic field used. Because of the complexity of the phenomena, the reader is referred to the complete report.[730]

2.3.2 Audio Noise Sources

A number of early investigations were made into the use of gas tubes as audio noise sources.[66, 190, 299, 305, 307, 467, 468, 639] One such study

considered the possibility of employing Tungar bulbs for this purpose;[305] it was concluded, however, that other tube types were better. Other studies led to the conclusion that the Types 2050 and 2051, and also the Type 884, were particularly suitable as sources of audio noise.[66, 307] These results brought about the development of several a-f noise generators.

Audio Noise Generator (Gaston)

One of the first audio noise generators, known as Gaston, was developed originally at the Bell Telephone Laboratories, Inc. As a result of early work on gas-tube noise generation,[66] the Gaston was designed with a Type 2050 tube as the noise source.[190]

Modifications to this design were made by Jansky and Bailey, to obtain a noise source for use in their vulnerability testing work[256] (see Sections 8.2.3 and 9.3).

Development of the device to the production stage was carried out by the Ballantine Laboratories.[306] This version of the Gaston consisted of a 2050 tube, transformer coupled into a single amplifier stage and operated directly from the standard 28-v d-c aircraft power system. The frequency range of the noise output was from 200 to 9,000 c, and the device delivered a maximum of 1.4 v to a 100-ohm load. It was used to modulate a standard radiotelephone transmitter by feeding the output into the microphone jack.[306, 307]

Magnetic Audio Noise Generators

On the basis of the work discussed below on the use of magnetic fields with hot-cathode arcs, two noise generators[574] were constructed to produce a flat noise spectrum in the range 500 c to 100 kc. These consisted of a 6D4 noise unit (see Section 2.3.4 below), a low-pass filter to remove high-level noise above 100 kc, and an amplifier.

In one unit, the amplifier was a single stage using a 6SN7 and a 4,000-ohm load; it gave an output of 180 v peak to peak. The other unit used one triode of a 6SN7 as an amplifier and the other as a cathode follower to generate 5 v peak to peak across 100 ohms. This latter generator was designed to operate into the microphone jack of a standard communications transmitter.

2.3.3 Study of Commercial Tubes

In addition to the investigations mentioned in the preceding section, a number of studies were carried out on the properties of commercial gas tubes as sources of video noise.[175, 299, 307, 566]

Studies of the Type 884

The early work consisted of several investigations of the Type 884 hot-cathode arc tube and similar tube types (including the 816, the 2050, and the 2051). Studies of the 2050 and 2051 tubes indicated that the noise output of these types fell off too rapidly at higher frequencies for them to be useful as video noise sources.[307, 639]

The 884 (and the 816) at first seemed to be the most promising. These tubes were shown to have relatively high-level noise output up to about 1 mc; at higher frequencies the noise decreased rapidly.[175, 346] Special versions of the 884 were examined[307] which contained various gases at various pressures, and the effect of using a transformer output coupling was investigated.

The variation of noise output from the 884 was studied in some detail with respect to pressure changes; it was shown that maximum noise for argon-filled tubes in the 2.5- to 5.0-mc band occurred at approximately 300 μ of mercury, with or without a magnetic field which aided in suppressing unwanted sustained oscillation.[299] Other gases were tried and the best results were obtained with helium at 700 μ, which, with a field of 80 gauss, gave a noise output equal to that of the argon-filled tubes with a 50-gauss transverse magnetic field. An attempt was made to interpret the source of the gas-tube noise and it was shown that random fluctuations in glow light output were directly related to the current fluctuations in the discharge in the frequency range, at least to 5 mc, a fact considered to be of significance in the understanding of the noise source.

In general, in the absence of a magnetic field, very strong sinusoidal oscillations were present. These oscillations are characteristic of the discharge and independent of external circuit parameters. They were as much as 40 db above the noise level and shifted in frequency from

tube to tube. The oscillations interfered seriously with the use of these tubes for noise generators.

Other Tube Types

It was discovered, however, that a transverse magnetic field would suppress the oscillations of many types of hot-cathode arc tubes and would also greatly increase the h-f components of the noise output. With this discovery a large number of commercial tubes were studied[566] in an effort to find the best possible source among tubes already in manufacture.[346, 348, 383-385, 467, 468, 473, 566, 639, 672, 769] The results of this study are summarized in Tables 1 and 2. Typical noise characteristics of four commercial tubes are shown in Figure 1.

2.3.4 Video Noise Sources

With the advent of the 2C4 and 6D4 miniature gas triodes the search for a suitable commercial tube ceased. The small size of this tube and the relatively low value of magnetic field required for optimum noise performance made it a very satisfactory noise source.

6D4 Noise Unit

The development was undertaken, therefore, of a unit noise source using the 6D4 in conjunction with a magnet. A small electromagnet and a permanent magnet were designed at RRL.[572] These magnets produced a flux density of 375 gauss at the tube. This noise unit made an extremely stable source, with variations of the

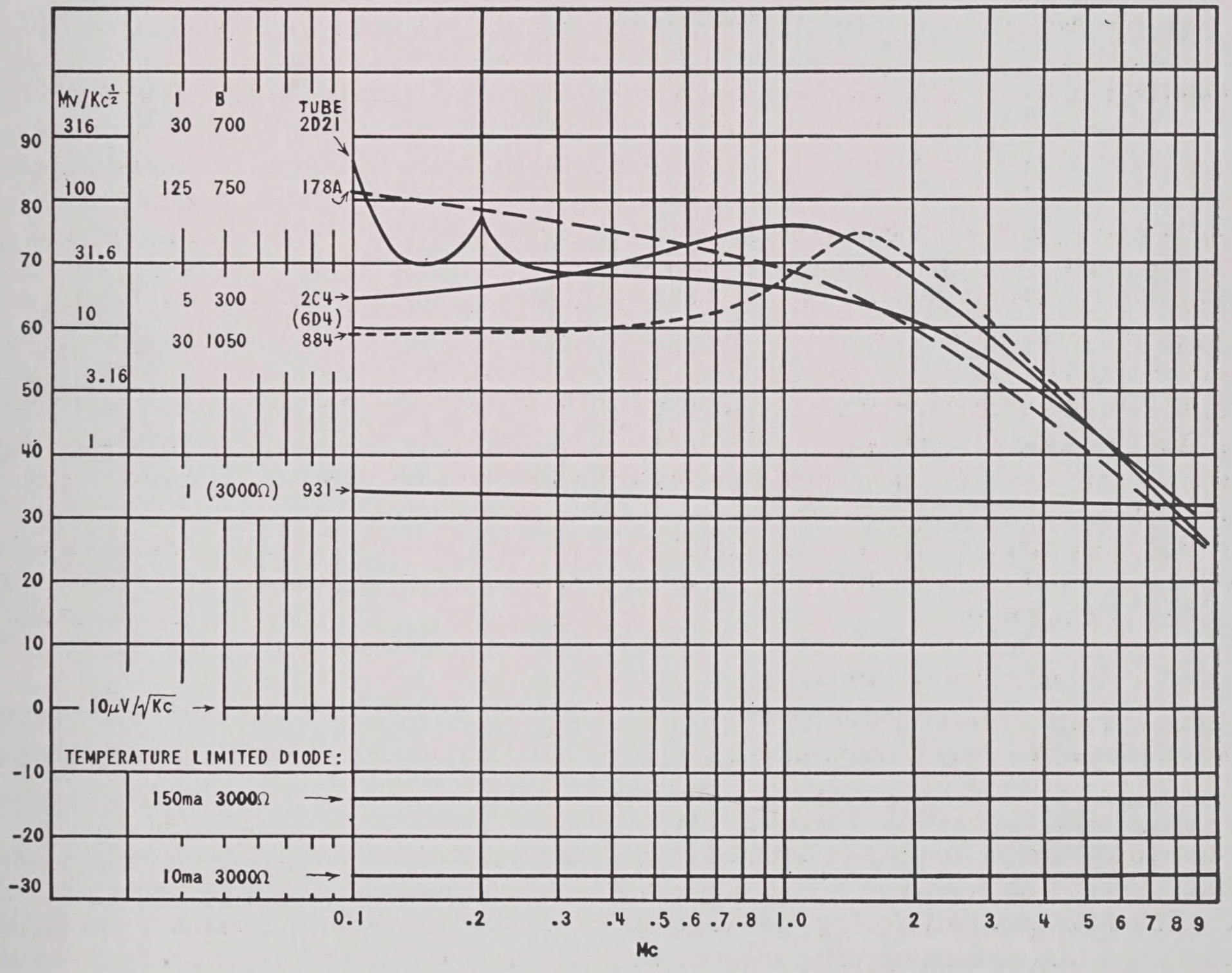


FIGURE 1. Typical spectra of hot-cathode arcs with transverse magnetic field.

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order of 1 db from tube to tube and practically no aging.[b] The relatively high noise output made possible the saving of one and in some cases two stages of video amplification in the noise modulators. At the end of World War II this noise unit had replaced most of the 931 sources in jamming modulators being manufactured.

This unit was a compact and reliable source of noise in the range from 0.1 to 5.0 mc for the initial stage of a modulator of a jamming oscillator. The field was provided by two collinear Alnico slugs mounted on opposite sides of the tube.

Redesign of the 6D4 Noise Source. In order to improve the mechanical design and reduce the weight of the unit developed at RRL, the General Electric Company undertook redesign of the unit. In the GE unit a ring magnet fitted concentrically over the 6D4 tube has been substituted for the two Alnico slugs. The ring magnet was mounted in a spun or die-formed circular aluminum housing consisting of a lower shield base, to maintain the magnet and tube socket in the preferred orientation, and a removable aluminum cover. This design required less mounting space, provided better shielding, and reduced the weight from 9 to 4 oz.

Flux plots of the ring magnet and of the collinear slugs showed that the field due to the ring magnet was much more uniform over the cross section of the 6D4 tube. It seems probable that this fact contributed to the uniformity of the output spectrum when the 6D4 was operated in the ring magnet at fields up to about 575 gauss. Operation at somewhat higher fields in a collinear electromagnet introduced a large oscillation peak around 0.4 mc. Operation at 575

TABLE 1. Summary of noise and oscillation characteristics of commercial gas tubes without transverse magnetic field.

Tube	Current (ma)	Oscillation: Fundamental frequency (kc)	Oscillation: Amplitude (db)*	Noise level (db)*: 50 kc	Noise level (db)*: 1 mc	Noise level (db)*: 5 mc	Rms noise voltage: 4 mc	References
Shot noise†	150	....	....	−14	−14	−14	41 mv	....
	10	....	....	−26	−26	−26	13 mv	
884	40	180	76	66	70	35	0.91 v	346, 468
	3	440	76	24	22	−8		
2A4G	100	450	52	50	24	−5	0.06 v	566
WL629	40	210	85‡	44	58	....		566
WE256A	75	120	51	38	40	−4	0.4 v	566
RK62	1.5	650	34§	....	1.0	< −10		566
2050	90	150	84	60	51	14		639
	3	90	78	36	14	< −10		
6Q5G	40	550	73	45	50	17		....
FG178A	125	100	78	....	38	0		348
2D21	41	85	94	≈80	54	18		383
816	125	170	67	≈60	37	9		

*Zero level = 10 $\mu v/kc^{\frac{1}{2}}$.
†Temperature-limited diode with 3,000-ohm plate resistor.
‡Second-harmonic amplitude 90 db.
§Probably another nonharmonic peak below 100 kc.

[b] Final design of assembly manufactured by the Cinaudagraph Corporation, Stamford, Conn., as Catalog No. 80-375.

gauss instead of 375 gauss has the advantage that the noise output is enhanced, particularly at the h-f end of the spectrum.

A modulator unit was constructed in which the noise unit drove an 807 modulator tube through two stages of 6AK5 miniature pentodes; the latter amplified the noise and compensated for the lower noise outputs at the high and low ends of the spectrum between 0.1 and 5 mc. This modulator delivered about 10 w of noise energy to a 1,000-ohm load.

Constriction Oscillator as a Noise Source

A constriction oscillator is a gas-discharge tube in which the arc passes through a narrow constriction between cathode and anode. As the arc current is increased, a critical value is reached beyond which the tube is unstable. In mercury vapor, for example, at 50 C (13 μ pressure), the critical current for a 0.040-in. circular constriction is 0.5 amp, corresponding to a current density of 60 amp per sq cm. It was thought that the output of such a tube operated in the unstable region might include a sufficiently broad and high-level noise spectrum to be useful in noise modulation of jamming oscillators.

Several varieties of constriction oscillators were built and tested,[128, 137] and noise power outputs of 30 w between 0.55 and 5 mc and of 4.5 w between 0.1 and 0.55 mc were achieved for power inputs of 125 w. This project was finally dropped for the following reasons.

1. Permanent gases like argon clean up very fast. Mercury vapor can be used but the tube output is very sensitive to the mercury vapor pressure and hence to tube temperature.
2. The tube life is only 5 to 10 hr, limited by cathode life.
3. The noise spectrum is nonuniform and erratic.
4. Standard tubes have been found elsewhere to be adequate for jamming noise sources.

Table 2. Summary of noise characteristics of commercial gas tubes operated with transverse magnetic field.

Tube	I (ma)	B (gauss)	V_p (volts)	Noise level (db)* 100 kc	1 mc	5 mc	Notes	References
6D4	5	375	8.2	63	76	38		384
(2C4)	5	720		66	76	43		385
	20	375		70	77	53	†	672
								467
884	45	1,050	5.6	56	62	48		346
								468
								639
2A4G	100	2,000	8.3	60	60	40		
WL629	40	2,500	4.4	71	69	43		
WE256A	75	2,000	....	65	58	33		
RK62	7	620	....	60	57	42	‡	
6Q5G	40	2,500	....	55	63	37	‡	
WE323A	100	1,800	....	62	44	8		
2050	75	500	....	74	47	13	‡	639
FG178A	200	960	9.9	82	70	43		348
2D21	41	1,200	5	72	70	47	‡, §	383
	30	700	5	70	64	46	‡, ‖	
GL546	13	740	....	68	70	48		473

*Zero level = 10 $\mu v/kc^{\frac{1}{2}}$.
†Standard RRL noise unit, Max = 80 db at 700 kc.
‡Oscillation not suppressed.
§Anode-to-cathode noise.
‖Grid as anode.

2.4 MECHANICAL AND OTHER NOISE SOURCES

A variety of noise sources were tried of types other than those discussed above. The more im-

portant of these were of a mechanical nature. In general, they were discarded as being less useful than the electronic sources discussed above.

2.4.1 Mechanical Noise Generators

Although a considerable number of different mechanical methods of producing noise were tested, the only one which gave any real hope

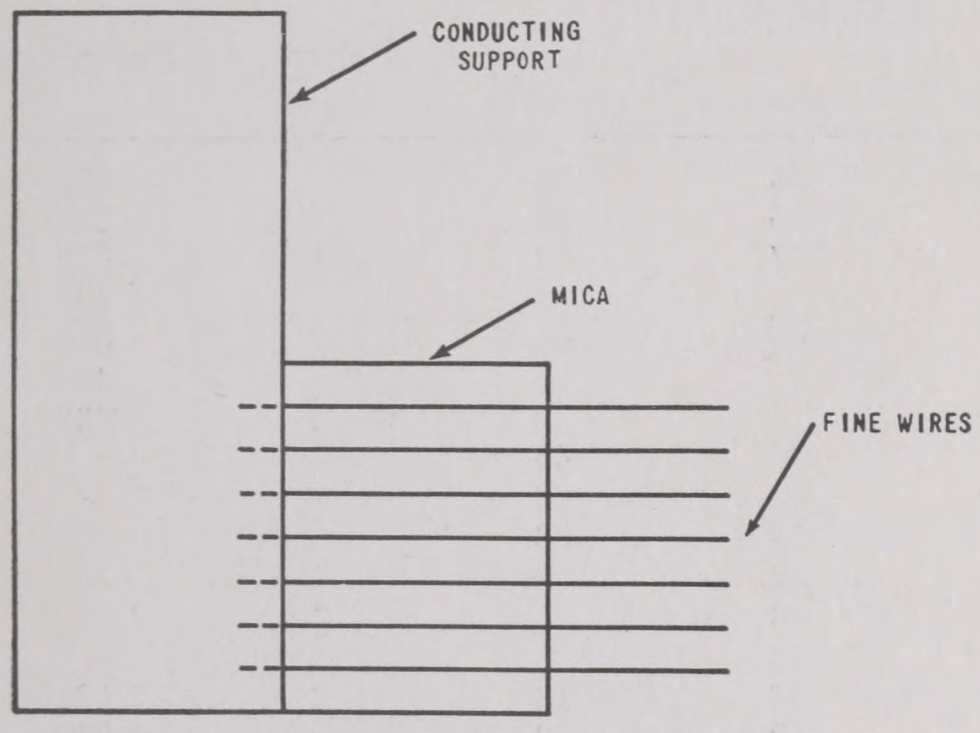


FIGURE 2. Detail of brush for Confuser-type mechanical noise source.

of success was the so-called Confuser. Among the other ideas investigated were the agitation of carbon granules carrying a current, two devices based on electrostatic generator principles, and the use of a buzzer.

MECHANICAL CONFUSER

The Confuser consisted of a carbon disk, or cylinder, mounted on the shaft of a small motor for rotation. The speed of rotation was relatively unimportant. (The data of the curves were taken for a speed of 1,800 rpm.) A low-voltage battery supplies current through a variable resistor to two brushes bearing on the carbon surface. Many kinds of carbon brushes, carbon granules, lead shot, copper braid, and other devices were tried as current collectors. The best response was obtained with wire brushes made of No. 38 Nichrome Grade D wire. Ten or fifteen strands of wire were used for each of the two collecting brushes. The individual strands were about 1 in. long and were cemented to a mica support so as to be insulated from each other, as shown in Figure 2. The brushes should have sufficient resistance so that the current in each wire is relatively independent of the current carried by the others. Figure 3 is the circuit used. The peak voltage depends somewhat on the supply voltage and series resistance. Thus, if only one wire is carrying current and the contact opens, at first the voltage across the brush is the arc drop. Then if the arc is extinguished the brush voltage rises to the battery voltage.

Output of the Confuser. When the brushes are both pressed hard against the surface of the rotating cylinder and carry a direct current of about 1 amp (much smaller currents may be used), the spectrum is as shown by Curve *A* of Figure 4. There are no peaks in the spectrum and the curve is smooth, as shown. When a light pressure is used, faint sparks develop at the ends of most of the wires and spectrum *B* results. When the pressure is very light, spectrum *C* results. For condition *C*, very random pulses occur; the peaks of the pulses equal the battery voltage. This condition of considerable sparking sounds like very good audio noise when phones are connected across the brushes. Unfortunately, no audio analyzer was available at the time this work was performed; consequently, audio spectrum can only be inferred from the trend of the video spectrum.

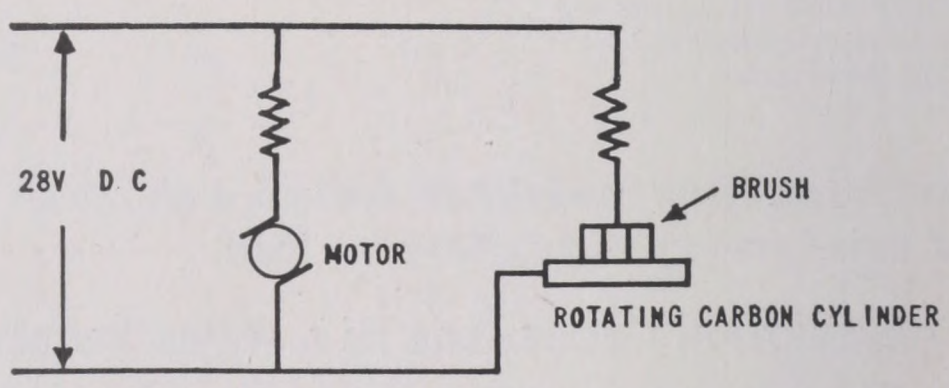


FIGURE 3. Circuit of Confuser-type mechanical noise source.

The greatest output voltage at 50 kc is obtained with a National Carbon C15 disk. However, there is no great variation of output with carbon. Carbons similar to National Carbon SA25 or SA45 sound very good in phones for condition *C*. An aluminum disk was tried, but it was found to have somewhat lower impedance

and less satisfactory noise characteristics than the carbon.

The photograph of Figure 5 shows the arrangement of parts of a working model. In this arrangement the carbon cylinder is mounted on the shaft so that the frame of the motor serves as one terminal. Some d-c motors produce considerable sparking noise. However, this "noise" has strong periodic components as a result of the rotational speed of the motor and the commutator characteristics. It might be satisfactory for some audio purposes.

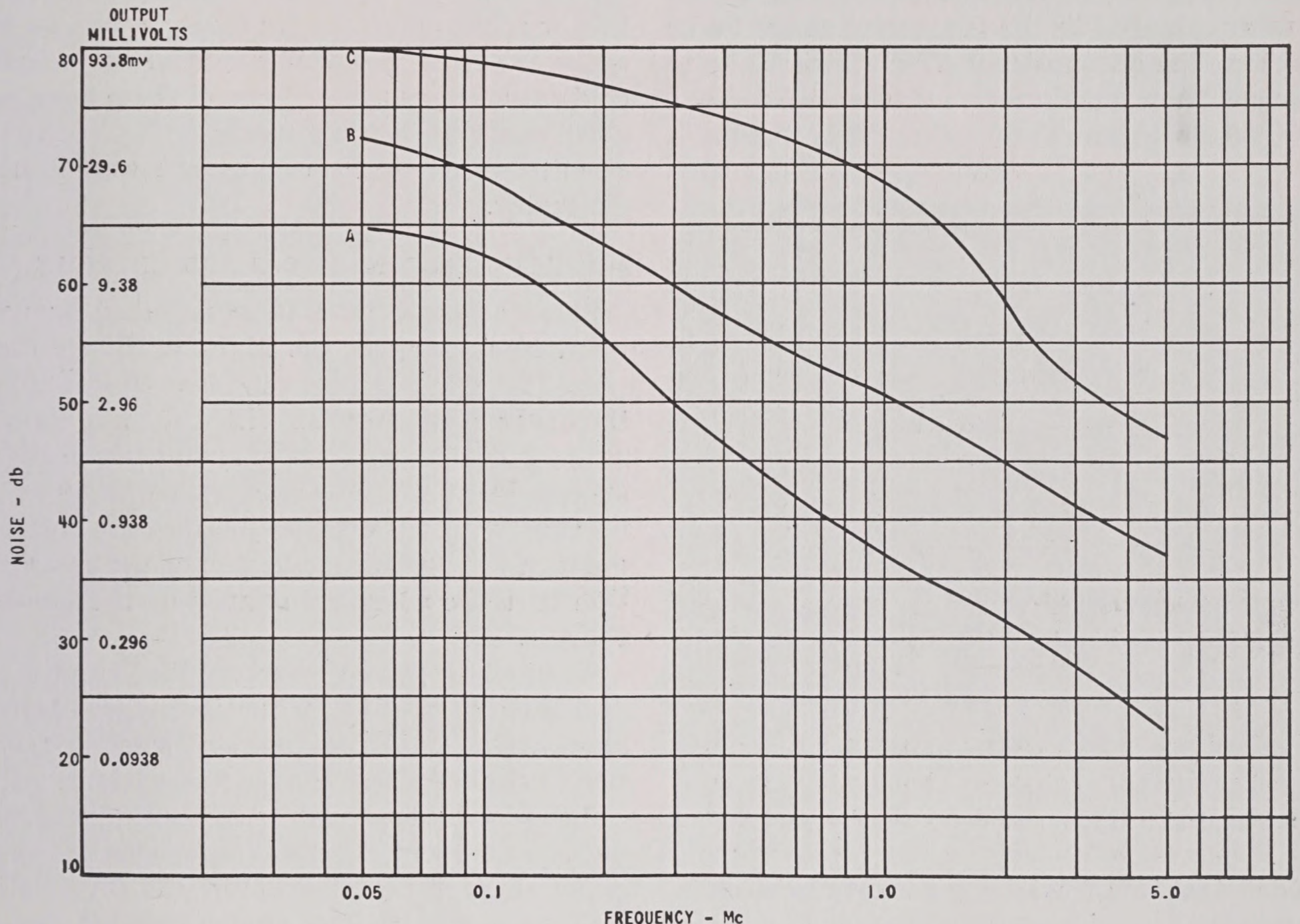


FIGURE 4. Spectra of Confuser-type mechanical noise source under various conditions of sparking. Curve *A* represents no sparking, curve *B* very faint sparks from all wires, and curve *C* very heavy sparking. Zero level for the decibel scale is taken as 9.38 μv.

OTHER MECHANICAL NOISE SOURCES

A number of other mechanical noise sources were tried and abandoned because of lack of promise. Among these were ideas for agitating carbon granules while they were carrying current. One of these consisted of an insulating cylinder filled with carbon granules and rotated by a synchronous motor, while current was passed through the granules by means of brushes bearing on conducting end-plates. Only l-f noise with occasional high peaks was observed for currents from 0.1 amp to 3 amp. In another device a rotating carbon cone or disk was introduced into a can of coarse carbon granules, but no improvement was observed.

Two mechanical devices based on electrostatic generator principles were tried. One of these consisted of a carbonized belt rotating between two conducting cylinders which were connected to a load resistor and source of direct current. No appreciable noise was developed by this device. The other consisted of a recirculating air stream driven by a small blower and carrying fine carbon granules (National Carbon Co.—UR80). Copper screens were placed across the air blast and connected to a load resistor and a power supply, as shown in Figure 6. Thus, par-

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ticles striking one screen would receive a charge and lose it when they struck the other, causing pulses in the load resistor. This device produced atmospheric-like noise with occasional strong bursts. The device did not seem to develop sufficient h-f noise for RCM purposes to warrant expending the time that would have been required to design an efficient system.

The noise output of a Speed-X Buzzer (1,000 c) was measured in the frequency range 50 kc to 5 mc. The output drops 37 db from 50 kc to 2 mc and then remains constant out to 5 mc at a level 30 db above 13.6 $\mu v/kc^{\frac{1}{2}}$. This source is

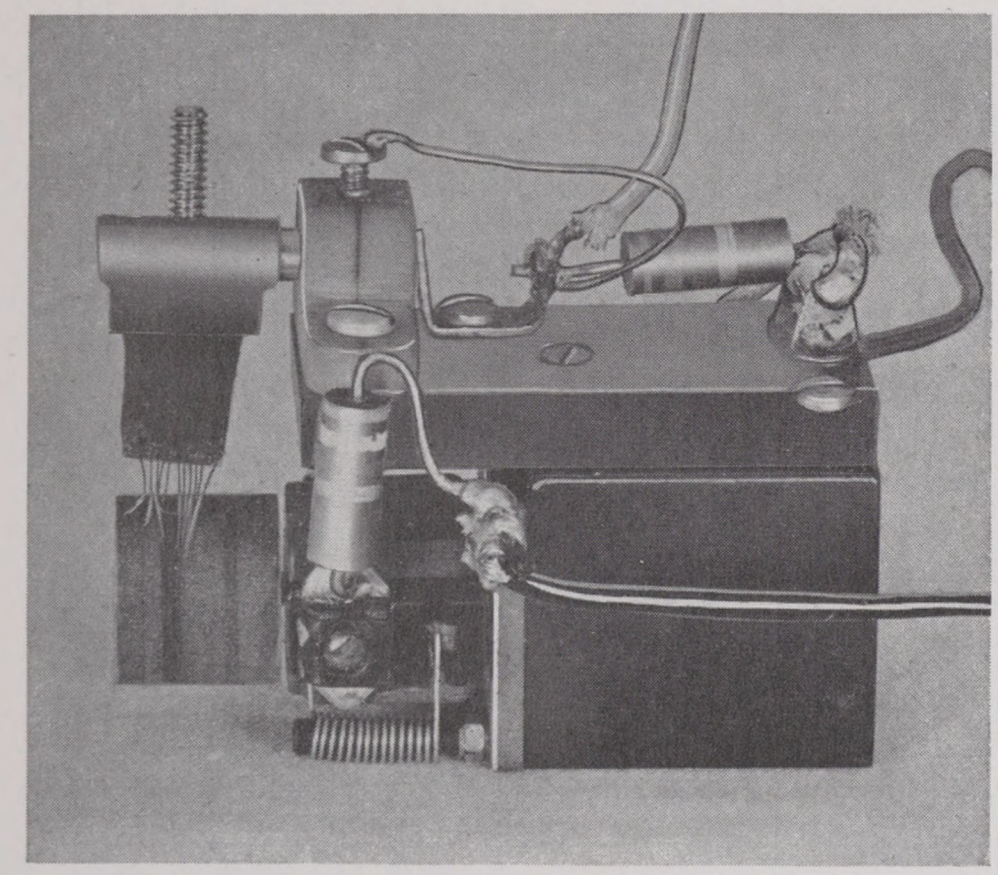


FIGURE 5. Photograph of the Confuser-type mechanical noise source.

too deficient in h-f noise components to be satisfactory.

A rotary spark-gap noise source was designed and two models were built.[307] The devices contained a pair of disks, one stationary and one which rotated, with studs spaced randomly around them. The first model employed a single ring (with 28 intervals between studs) on both rotor and stator, the second used three concentric rings on each (with 28, 20, and 17 studs). The studs were distributed according to a nongaussian exponential law; after the calculation of the proper number of irregular intervals, the order of the intervals was chosen on a pure chance basis. The preliminary tests indicated good properties as a noise source for communications jamming but indicated that an even greater number of separate stages (sets of rings) would be desirable.

2.4.2 Other Noise Generators

Among the other types of noise sources investigated were the possibilities of using crystals or semiconductors for this purpose, as well as a variety of miscellaneous sources including cold-cathode gas tubes. None of these were very good, except that an electrolytic interrupter circuit offered some promise as an audio noise generator.

Noise in Semiconductors and Crystals

Some crystals have been reported as noisy when conducting in the high-impedance direction. The noise level is very low (2 $\mu v/kc^{\frac{1}{2}}$), of the order of diode noise with 150-ma plate current (see below). However, the low level observed in the preliminary tests of crystals, thermistors, and resistors justified the abandonment in the preliminary stage of the investigation of these sources in favor of the gas-tube sources.

Electrolytic Noise Sources. Electrolytic condensers give some l-f fluctuations when operated above their rated voltages. Electrolytic solutions exhibit no appreciable fluctuations.

The possibility, however, of obtaining random pulses of current at audio frequencies by means of an electrolytic interrupter was investigated in some detail.[307] The study included the examination of the effects on the spectrum and output voltage of electrolyte concentration, the use of detergents, electrode material and construction, current density, and so forth. It was found possible to obtain outputs of 3 v or 4 v rms into a 1,000-ohm load with a spectrum essentially flat from 100 c to 16 kc; beyond 50 kc the attenuation was too high for the output to be useful. The physical problems involved in the design of a compact electrolytic cell providing protection against decomposition, gassing, spilling, and freezing, as well as stability under vibration and tilting, caused the project to be dropped in favor of the gas-tube audio noise generator.

Miscellaneous Noise Sources

Several miscellaneous types of noise sources which were considered and discarded are described in the following paragraphs.

Cold-Cathode Gas Tubes. The low-pressure glow discharge was found to generate noise under certain conditions.[737] The noise of this type of discharge could be increased by a transverse magnetic field. However, the high voltage required to maintain this discharge made it unsuitable for noise generator applications. The low-pressure mercury-cathode arc generated both noise and oscillations but was generally unsatisfactory. This latter tube had two mercury-pool electrodes and was used as a "shorting" bar on a split-anode magnetron tuning bar. The action of the discharge caused some random shifting of the operating frequency. However, the rate of shifting was too low for direct modulation purposes and there was insufficient time to develop the device. A corona tube was constructed with a fine wire inside a glass tube as one electrode and the surrounding ground plane outside the envelope as the other. This tube required high voltage and gave only random pulses due to electron avalanches.

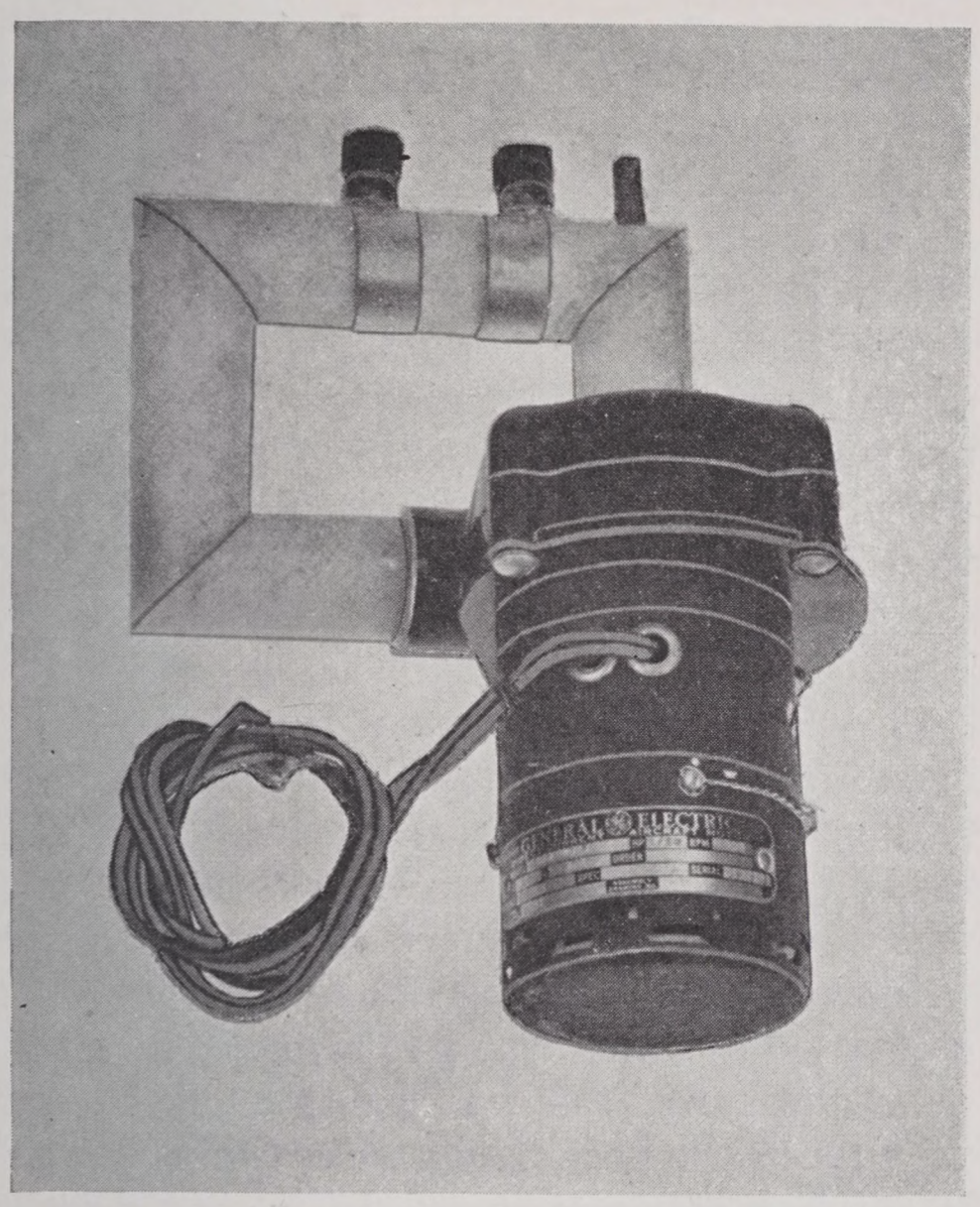


FIGURE 6. Photograph of the air-blast type noise source.

Moving Arc. An attempt was made to develop noise by means of a continually moving arc operating at atmospheric pressure. A d-c arc was established between a carbon disk and a brass ring. It was intended to rotate the arc around the disk by a radial magnetic field. However, it was found that the magnetic field necessary to rotate the arc would require an excessively large exciting magnet. Such noise as was observed was of low level and apparently deficient in h-f components.

Diode. A wide-band (60-mc) amplifier was constructed, with a tungsten-filament diode (Type CV172) of low capacitance and a cathode-follower output stage. Since the noise output characteristics of a temperature-limited diode (i.e., maximum anode current, as determined by cathode emission, is drawn) may be calculated analytically, this device was useful in calibrating the video spectrum analyzers.

2.5 NOISE-MEASURING TECHNIQUES

In order to compare various noise sources and to measure their outputs and spectra, techniques of noise measurement had to be developed. This work involved a theoretical analysis of the nature of noise and the design of a number of devices for noise measurements.

The experience in circuit techniques for noise which was gained in this way was applied to the development of equalizing circuits for noise amplifiers.

2.5.1 Theoretical Analysis of Noise

An extensive analysis showed that noise differs in many important respects from periodic waves and single transients.[758] Although many of these differences have been noted, no comprehensive attempt has been made to outline the restrictions necessary in the application of standard circuit theory to noise, and to establish the basic and useful rules for practical applications.

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In the report on this analysis,[758] frequently used quantities of measurement and description, such as average, mean square, and peak value, were summarized and their application to noise and to periodic waves compared. The main point of difference is that, whereas for periodic waves these quantities are exact and invariant with time, for noise they are to some degree diffuse and fluctuate with time. Whereas the instantaneous time function of a periodic wave can always be expressed analytically (by means of the Fourier development), the time function of noise generally cannot. Consequently, the only quantities available for analysis are time averages.

Theoretical and experimental work on the effect of nonlinear distortion on the power spectrum is summarized. The theory developed is applied to problems in the measurement of noise. In this connection, Section 6.2 should be consulted also.

2.5.2 Noise-Measuring Devices

In the course of the experimental study of noise it was necessary to construct a number of noise-measuring devices.

Video Spectrum Analyzers

A video spectrum analyzer (H100) was designed for measurements in the range 100 kc to 9 mc. It was essentially a wide-range receiver designed to measure noise in this frequency range.[595] A cathode-follower probe provided a high-impedance input, and a square-law power output meter measured the energy in either an 11-kc or a 33-kc band. Provision was made in the experimental model for a panoramic view of the spectrum from 1 mc to 5 mc. At maximum sensitivity the instrument could measure a noise input level of 3.5 $\mu v/kc^{\frac{1}{2}}$ (100-ohm input) or 10 $\mu v/kc^{\frac{1}{2}}$ (50,000-ohm input). In operation, the actual sensitivity is controlled by means of two calibrated attenuators. The gain is constant to 1 db from 100 kc to 9 mc, and the original unit would measure a peak of 5 v without distortion. Two of these units were constructed at RRL. The analyzer was not designed to measure voltages with waveforms having large peak-to-rms ratio (such as radar pulses).

A similar video analyzer[307] was developed to cover from 30 kc to 10 mc. It had a bandwidth of about 10 kc and at maximum sensitivity could measure signals of less than 10μv. It overloaded, however, with peak voltages of about 1 v—considerably less than the reported value. This equipment was transferred from Ballantine to RRL, where (since the response was not rms) it had to be calibrated with the H100 analyzer.

In order to assist in the investigation of 931 and other noise sources, a video spectrum checker (H300) was developed.[830] This consisted of a cathode-follower input probe, attenuator, video amplifier (0 to 5 mc), low-pass filter (0 to 2.5 mc), high-pass filter (2.5 to 5 mc), and thermistor bridge bolometer for measuring the output current. The device was useful in determining the level of noise and its trend with frequency.

Audio Spectrum Analyzers

Several l-f spectrum analyzers were developed for research and to aid in determining the best operating conditions for the 884 used in the B3207 modulator. One of these (H500) covered the frequency range 500 c to 200 kc,[550] with a measuring pass band of 60 c, which could be located anywhere in this range. The instrument measured the rms value of noise components in the pass band, with a sensitivity of 100 $\mu v/kc^{\frac{1}{2}}$. The instrument comprises a cathode-follower input probe, an attenuator, a high-pass filter, one stage of preamplification, a modulator, and a local oscillator followed by a low-pass filter, an l-f amplifier, and a rectifier and meter.

Another l-f analyzer[665] was designed to extend the range of the General Radio Sound Analyzer 760A (normal range 25 c to 7 kc) to 200 kc. This was accomplished by means of an oscillator and a tuned mixer to beat the noise at high frequencies down to a fixed frequency band in the range of the sound analyzer centered either at 500 c or 2,000 c. High input impedance was provided by a cathode follower. The minimum detectable sine-wave signal was 0.82 mv. Although intended for the range 7 kc

to 200 kc, the response was flat to 1 db from 15 kc to 1 mc. Since the response of the General Radio sound analyzer is not rms, it was calibrated by comparison with H100.

Two other audio analyzers were developed.[307] The first of these covered from 1 kc to 100 kc with a bandwidth of either 150 c or 250 c and a sensitivity of about 100 μv. The other operated in conjunction with a Hewlett-Packard wave analyzer, from 200 c to 16 kc. The bandwidth was continuously variable from 60 c to 360 c, and signals between 0.1 mv and 500 v could be handled.

Peak-Reading Voltmeter

A peak-reading voltmeter (H205) was developed especially to meet noise requirements.[520] The meaning of "maximum value" is vague when applied to a function, such as random noise, whose future progress is unpredictable; hence, an arbitrary criterion is required to define peak voltage. For pure noise (i.e., with a gaussian amplitude distribution), the effective peak value is for many applications proportional to the rms amplitude, which can be accurately measured with a square-law meter. For asymmetric, clipped, highly pulsed (in general, nongaussian) noise, however, the proportionality between rms and effective peak amplitude breaks down, and direct measurement of the peak is required. Furthermore, with unsymmetrically clipped noise both positive and negative peaks must be measured. For the instrument developed, a practical criterion of peak voltage was selected in terms of linear-diode clipping. It was found that a diode loaded by the input circuit of a cathode follower possesses approximately constant-current characteristics. The circuit constants were chosen so that the average load current was small and underwent very small variations as a function of input voltage. The average output voltage defines the "peak" voltage. The voltmeter measures peak-to-peak voltages from 1 v to 150 v and covers the frequency range 50 c to 30 mc.

Tube Testers

The investigation of the 931 characteristics (Section 2.2) which revealed the great variations existing among individual tubes and their aging characteristics demonstrated the need for a special tube tester for this photocell. The 931 Tube Tester, Type U400, consisted of a light source, voltage divider, and power supply for the tube under test which were essentially like those of most 931 noise modulators. A video amplifier and vacuum-tube voltmeter completed the instrument. Provision was made for standardizing the 931 plate voltage and anode current so that the noise output voltage was a measure of the gain of the tube.

A checker (H206) was developed[756] for the 6D4 tubes so that the manufacturer (Sylvania) could ascertain the noise quality of his tubes. This device measured the noise output in a band centered at 200 kc (characteristic of the l-f level) and at 3 mc (characteristic of the h-f level), and also integrated the noise output for all frequencies below 5 mc (indicative of the "drive"). Improperly activated cathodes could be detected by this checker.

Throughout much of the work, the rms value of noise voltage was measured by means of a cathode follower with a thermocouple in the output circuit. The bandwidth of the unit was 15 mc and it presented the necessary high impedance at its input terminals.

2.5.3 Noise Equalization

The noise output of the gas-tube sources, such as the 6D4 noise unit, requires both amplification and equalization in order to provide a suitable spectrum for modulation.[723] This fact required the development of techniques that departed from the usual video ones. Ordinary video amplifiers operate Class A and are adjusted so that they do not have frequency or phase distortion or nonlinear distortion. Noise amplifiers are overdriven, as a rule, in order to get clipped noise; thus, nonlinear distortion is present. Compensation networks are used to eliminate frequency distortion but not phase distortion.

Equalizing circuits for noise amplifiers must, to a large extent, be adjusted empirically because (1) grid current is drawn and (2) clipping[589] causes an increase in the l-f and h-f noise components.[596] For raising the h-f noise

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level, a simple shunt or series peaking circuit is satisfactory. The former, serving as the load of the first amplifying tube, must be used to compensate for the drop-off in the spectrum of the 6D4 standard noise source. The series circuit can be used to compensate for intertube capacitances. Low-frequency compensation can be achieved by using a parallel RC circuit in series with the load resistance of the tube.

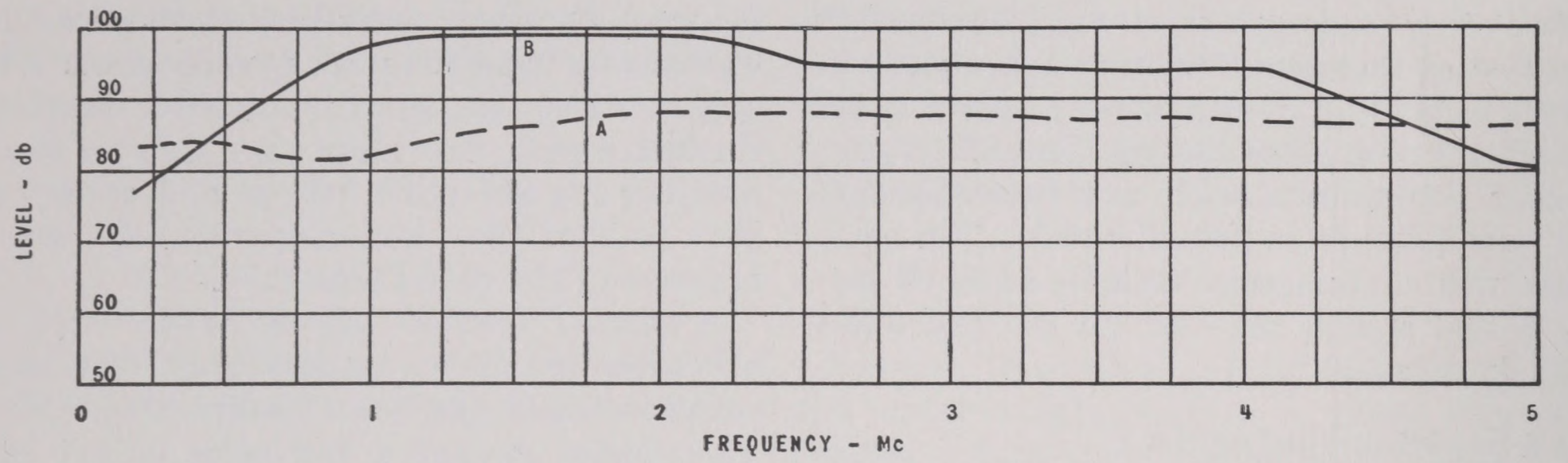


FIGURE 7. Comparison of sine-wave and noise tests of an amplifier. Curve *A* shows the actual noise spectrum; curve *B* shows spectrum that would be expected from sine-wave tests. (Zero level = 10 μv/kc½.)

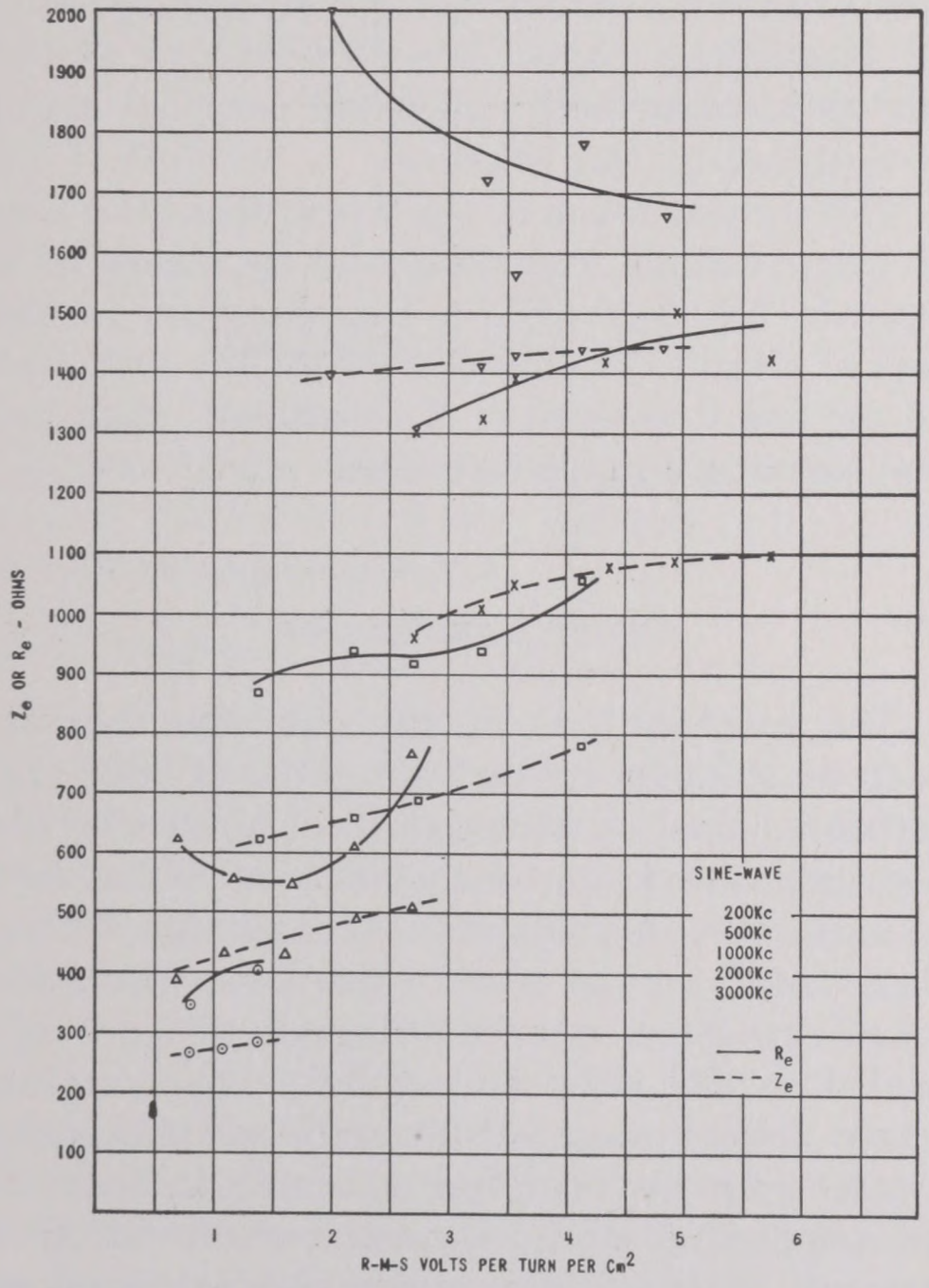


FIGURE 8. Effect of sine-wave excitation on core impedance and resistance. The following symbols are used: ⊙—200 kc; △—500 kc; □—1,000 kc; ×—2,000 kc; and ▽—3,000 kc.

Equalization should be done with noise voltage and a spectrum analyzer. It is usually not satisfactory to equalize a noise amplifier by the use of sine-wave and ordinary video-amplifier techniques, because the dynamic operating conditions change considerably when noise is amplified. This is illustrated in Figure 7, where curve *B* shows the spectrum that would be expected from sine-wave tests of a modulator, whereas the actual noise output spectrum was as given by curve *A*.

2.6 VIDEO NOISE TRANSFORMERS

Transformers as coupling elements are used chiefly in driving push-pull amplifier stages and in coupling power stages to low-impedance loads. These two applications are widely used in a-f amplifiers, and the problems of designing suitable transformers in that frequency range are well understood. If it is necessary to use transformer coupling in a broad-band amplifier which must pass frequencies from several kilocycles to several megacycles, a number of problems arise which cannot be answered without much investigation of transformer materials. If the transformers are required to pass wide-band random noise, the problem is further complicated, since it cannot be assumed that the performance of a transformer with sine-wave is an accurate index of its behavior with noise excitation.

A project was therefore undertaken[742] with two general objectives: (1) to make a thorough study of the properties of transformer iron at frequencies up to 5 mc, for both sine-wave and noise excitation, and (2) to make use of this information to design suitable interstage and output transformers for a Class B wide-band noise amplifier.

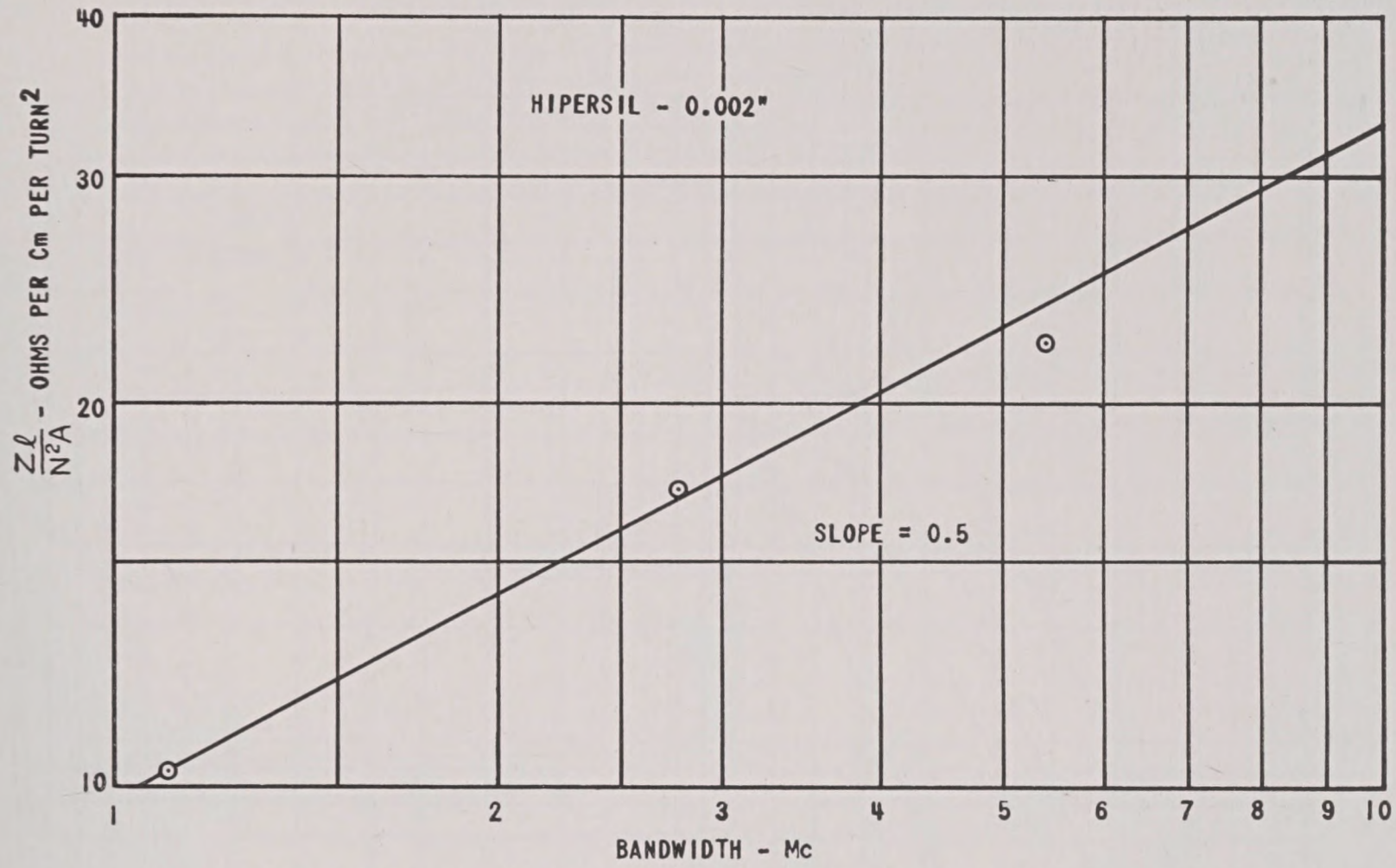


FIGURE 9. Specific impedance of a transformer core as a function of the bandwidth of the exciting noise.

2.6.1 Transformer Materials

In general, there are two major points to be kept in mind in choosing the type of transformer iron to use. The first is the desirability of keeping the power loss in the iron, due to both hysteresis and eddy currents, to a minimum. A theoretical analysis[761] of eddy-current losses in transformers is described in Section 6.2.3. The second important point is the desirability of low current in the transformer windings—that is, high exciting impedance, to minimize copper losses.

The investigation was confined to relatively few kinds of transformer iron. The cores studied were supplied by the manufacturers in finished form ready for winding. The material studied most thoroughly was Hipersil, as used in the standard Type C core made by Westinghouse Electric Company. Some measurements were also made on Permalloy-ribbon cores of similar construction. The other materials studied were Monimax and B9W4A, a nickel-silicon-iron alloy. These materials were available in standard punchings, which were stacked to form cores of the desired size. The thickness of the laminations was as follows:

Hipersil	0.001 in. and 0.002 in.
Permalloy	0.001 in.
B9W4A	0.004 in.
Monimax	0.003 in.

EXPERIMENTAL RESULTS

Measurements were made of the exciting impedance of the cores and of the core losses, for both sine-wave and noise excitation.

Impedance Measurements. Practically all of the impedance data were obtained with Type C Hipersil cores of various dimensions. For the most part the Hipersil was 0.002 in. thick, although some information was obtained for 0.001-in. Hipersil.

The exciting impedance (and resistance) was measured as a function of frequency for both sine-wave and narrow-band noise excitation, for a wide range of values of all the param-

eters involved. Typical results are shown in Figure 8, which gives some impedance values for a Hipersil core. These curves were obtained with sine-wave excitations and show how the impedance and effective resistance vary with excitation for different frequencies. The impedance is very little dependent on excitation. This fact simplifies the investigations considthat the impedance is nearly proportional to the square root of the bandwidth, as long as the frequency is not high enough to permit shunting capacities to be important.

Core Losses. Measurements were made of specific core loss as a function of excitation by sine waves and by noise. The materials studied included Hipersil, Permalloy, Monimax, and

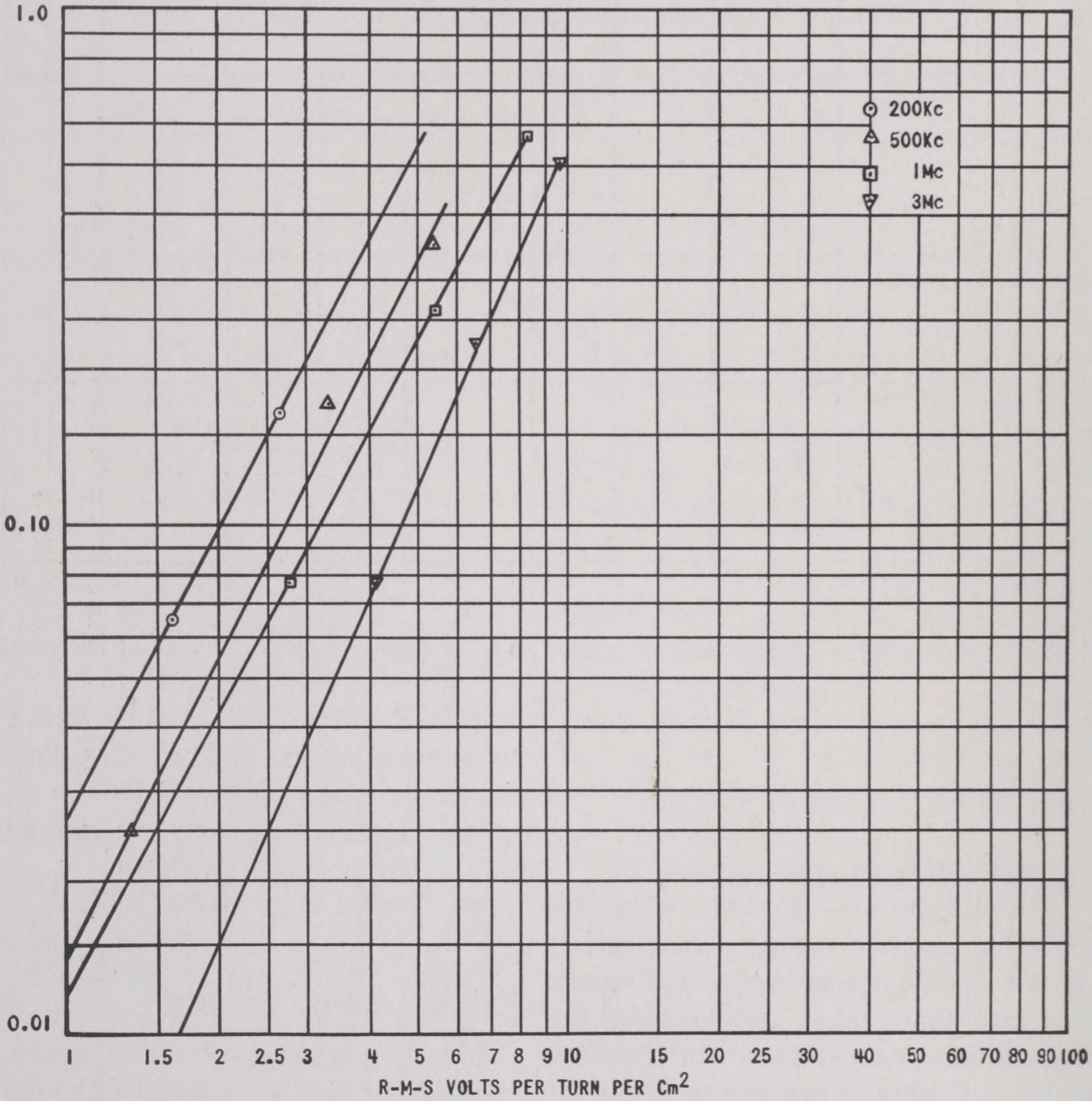


FIGURE 10. Loss curves for 0.002-in. Hipersil, sine-wave excitation.

erably. It will be noted that both the impedance and the resistance increase with increasing frequency.

The wide-band noise impedance was investigated as thoroughly as the narrow-band. The dependence of wide-band impedance on bandwidth is shown in Figure 9 for one coil. The line is drawn to have a slope of 0.5. The near coincidence of the points with the line shows

B9W4A. Typical loss curves for sine-wave excitation are shown in Figure 10, for 2-mil Hipersil.

Typical core losses for noise excitation are shown in Figures 11 and 12. The former is a comparison between the losses in 2-mil Hipersil, 4-mil B9W4A, and 3-mil Monimax. The comparison was made on this seemingly illogical basis because these three are available in suffi-

cient quantity to meet production demands. The Monimax appears to have the lowest loss. Figure 12 shows the losses in 3-mil Monimax with excitations of different noise bandwidths. The losses in general decrease as the bandwidth is increased at constant excitations; in fact, the loss appears to be inversely proportional to the square root of the bandwidth. In other words, as the energy in the h-f components increases at the expense of the l-f components, the losses are due largely to the l-f end of the noise spectrum.

The dependence of loss on the excitation and the bandwidth appears to be in qualitative agreement with the results of the theoretical analysis.

Other Measurements. An attempt was also made to separate hysteresis from eddy-current losses by combining the results from the theory of eddy-current losses with rough estimates of the hysteresis losses made on the basis of a series of permeability and hysteresis measurements. The attempt was only partially successful, but it was possible to obtain approximate estimates as to the proportional division of the losses.

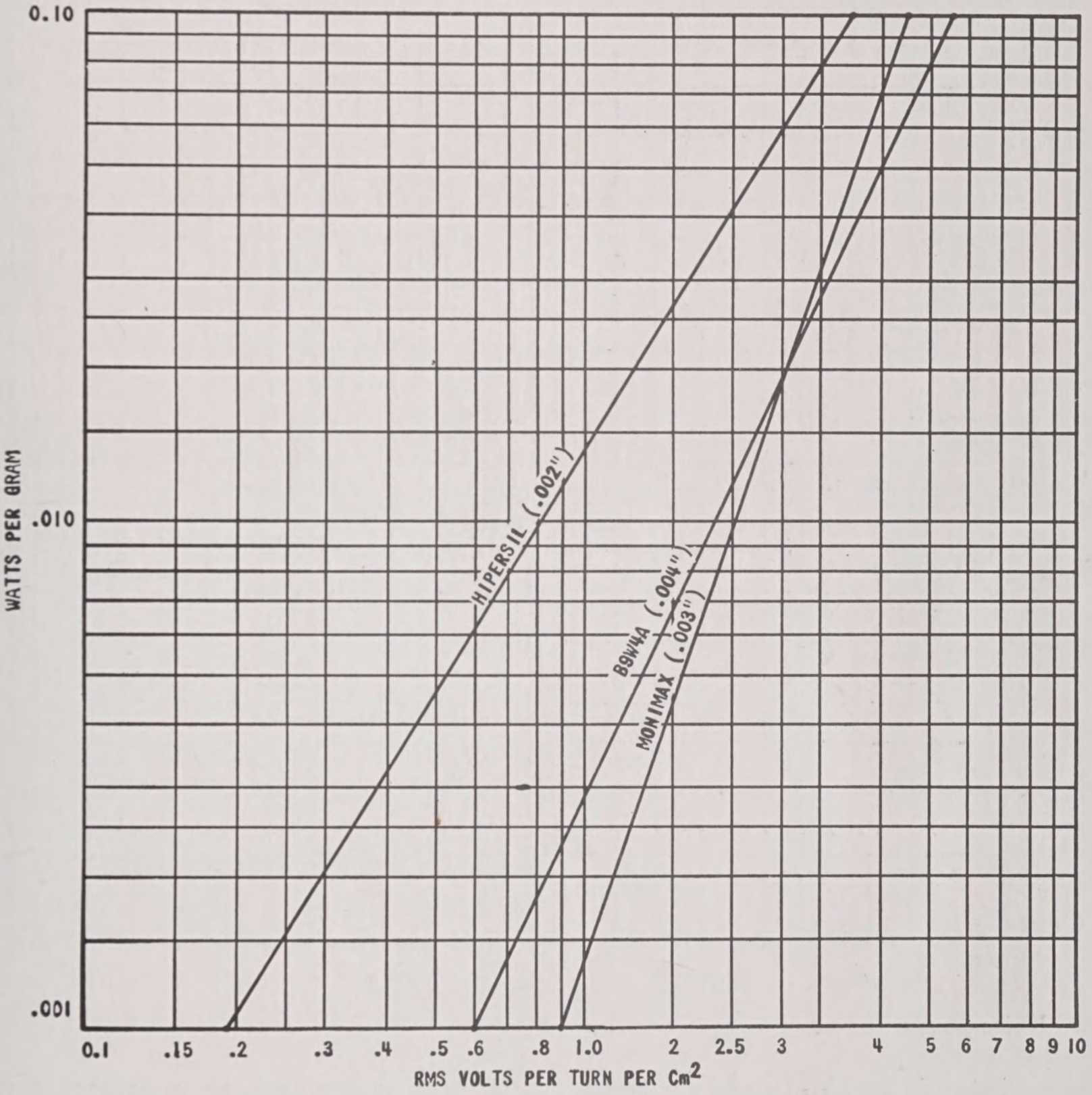


FIGURE 11. Noise losses in various materials for 0.1- to 2.5-mc band.

The effect of a superimposed d-c magnetizing force on the a-c losses was checked and found to be very small, even when the d-c field was many times greater than the a-c.

It was found also that an air gap in the magnetic circuit increases the magnetizing force and decreases both the impedance and the core losses.

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2.6.2 Transformer Design

The information obtained about transformer iron is directly applicable to transformer design in general. The transformers discussed in this section were intended to be used in a Class B modulator with wide-band noise excitation. There are thus a number of complicating problems to be solved simultaneously.

The method of approach to the problem of designing a transformer for a specific purpose is illustrated by the work done in developing two transformers for a noise amplifier.[742] This development is therefore described here in some detail.

Design of Transformers

It was desired to design two different transformers for use in a Class B power amplifier for noise. The required bandwidth was 2.5 mc, and it was desired to obtain 350 w of noise power in a 50-ohm resistance load. The power stage was to consist of four 813 tubes in push-pull parallel.

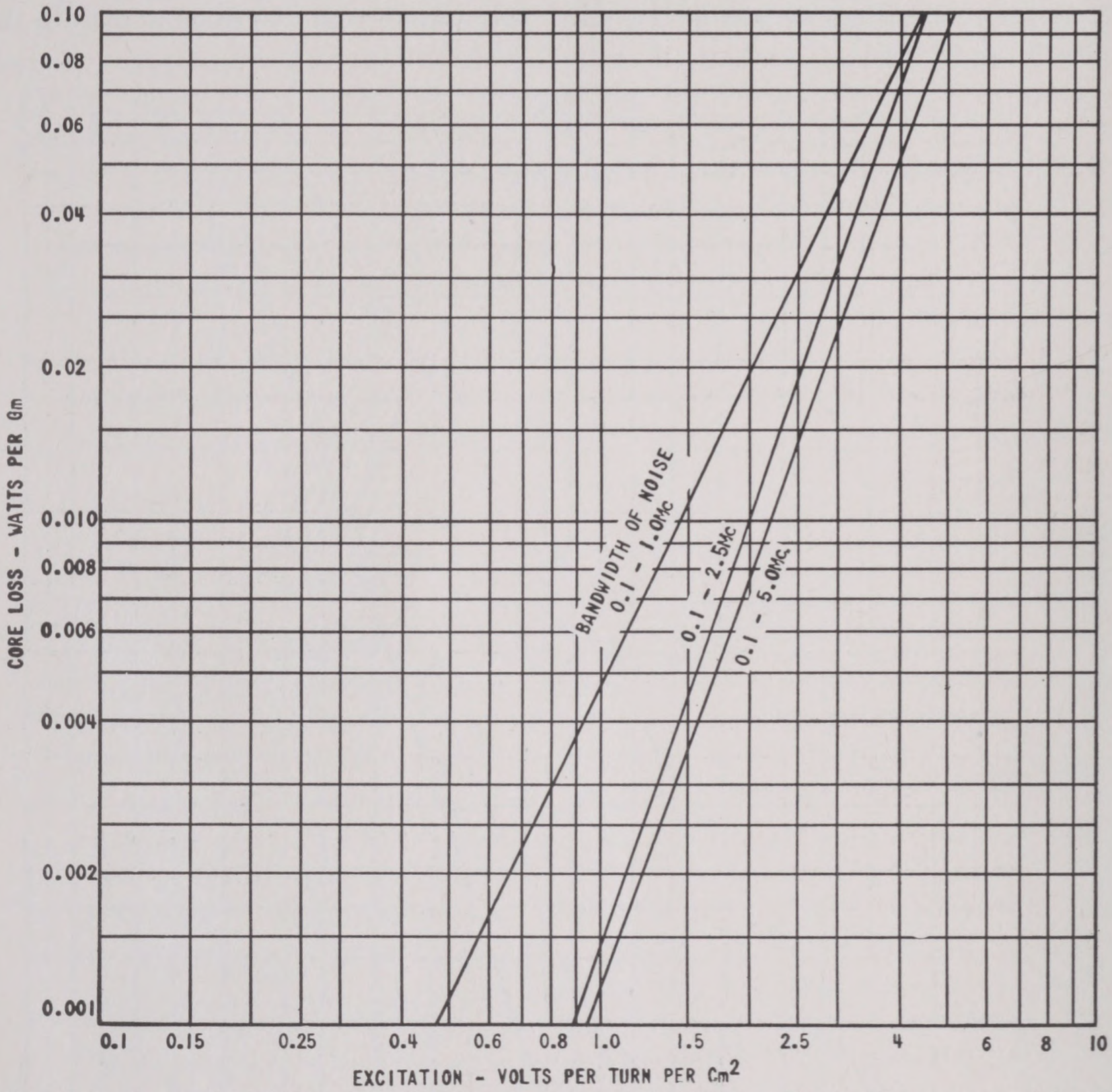


FIGURE 12. Noise losses in 0.003-in. Monimax for various bandwidths. Excitation measured in rms volts.

The interstage driver or preamplifier output tube was a single 813.

The design of the interstage transformer was not carried to the optimum point because the proper impedance on the secondary side was never definitely determined. There were problems involved here of clipping in the preamplifier and in the grid circuit of the push-pull stage. Much work remained to be done in balancing the various conflicting factors.

The particular transformer used in these tests was of shell-type construction, using four 2-mil Hipersil cores (½x½-in. cross section,

½x1⅛-in. window). The impedance seen by the secondary was arbitrarily chosen as 4,000 ohms, shunted by the indeterminate effective resistance of the grid circuit. Experience indicated that the total effective grid-to-grid impedance was about 3,500 ohms. A resistance of about 3,500 ohms was found to be a suitable plate load for the driver 813, so a total turns ratio of unity was chosen. Of course, the 4,000 ohms chosen for the secondary could have been decreased with decreased output voltage, or increased with decreased bandwidth. The primary consisted of 120 turns of No. 40 Formax wire, reverse-wound and paralleled; and the secondary consisted of 120 turns of No. 36 Formax, center-tapped. The core impedance at 100 kc was 37,000 ohms. The exciting voltage across the primary was 735 v rms. This voltage should result in a core loss of about 9 w. Further investigation of the effects of clipping in the preamplifier showed that a lower excitation voltage was adequate to produce the required power output. Unfortunately, time did not permit completion of a design to meet the new specification.

The design of the output transformer was more straightforward because the secondary voltage (132 v) and load resistance (50 ohms) were specified. From consideration of the tube characteristics, a plate-to-plate impedance of 3,200 ohms was thought desirable, so the turns ratio was fixed at 8. The primary excitation voltage obtained by multiplying the corrected secondary voltage (to account for losses) by the turns ratio was 1,225 v. Monimax was chosen as the core material because of its low losses. The limited selection of available Monimax punchings forced the choice of a core having a magnetic path about one-third longer than was required by a reasonable winding length. The longer path would require a lower excitation E in order to keep down the total losses. If E/NA is taken very conservatively as 1.5, NA must be of the order of 800 ampere-turns. The exciting impedance Z was chosen to be about 30,000 ohms. The value of Z/N^2A for Monimax at 100 kc was found to be 0.64, so that N^2A must be of the order of 5×10^4. Solving for N and A, one obtains values of 60 turns and 12 sq cm, approximately. Actually, it was found that a somewhat larger number of turns could be used without disturbing the h-f characteristics. The number of primary turns was set at 80, with 10 turns on the secondary, so that a smaller amount of iron could be used. The cross section chosen was 9.65 sq cm. The primary was wound with No. 38 Formax, while the secondary was wound with No. 24 Formax and contained two windings of ten turns, reverse-wound.

A feature of these transformers was the insulation used between windings. The usual dielectrics were found to be unsuitable because of the h-f loss characteristics and the low maximum temperatures tolerated. The insulation finally used was Poly F-1114 (Teflon, a low-loss material with high dielectric strength 1,000 to 2,000 v per mil) and a maximum tolerable temperature of 300 C. Teflon is available in tape form of any desired width, with a minimum available thickness of 5 mils. Two thicknesses of the 5-mil tape were used in each transformer to separate the windings. This permitted very low leakage reactances, although the capacitances were undoubtedly somewhat increased. The optimum thickness must be obtained by a trial-and-error process. Since the Teflon is very slippery and does not adhere to any known cement, it was necessary to devise special clamps to hold the insulation in place. The clamps were also used as terminal boards for the winding ends.

Tests of Transformers

The transformers described above were tested for frequency response, loss characteristics, temperature rise, and overall performance. The preamplifier stage consisted of a 6D4 gas-tube noise source, followed by a 6AB7, a 6L6, and an 813. The modulator stage contained four 813 tubes in push-pull parallel. The preamplifier design was based on much experience with similar circuits used in Class A modulators.[723]

The transformers appeared to be satisfactory in their ability to transform the required amounts of power with good fidelity and without excessive losses. It was not possible to obtain adequate spectrum measurements on the high-impedance sides of these transformers because of distortion introduced by the shunting capacitances of the measuring equipment. A

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lack of flatness in the spectrum was caused by the preamplifier. It was not found possible to obtain a flat spectrum at the required power level, i.e., 350 w. The actual sine-wave response of the transformer was flat to within 2 db over the required range; however, the effect of the various causes of distortion was to make the overall spectrum produced flat only to within 5 db over the frequency range.

The actual power lost in the transformers was measured in a crude calorimeter which was probably accurate to at least 20 per cent. With a load power of 380 w, the output transformer had a loss of about 45 w. The total input power to the plates of the push-pull tubes was 840 w. Hence, the plate dissipation was about 415 w, which is just about the limit for four 813's (rated dissipation, 100 w per tube). The plate efficiency was about 51 per cent, with an overall plate-circuit efficiency of 45 per cent. The losses measured in the input transformer for this condition were about 6 w.

A second check on the heat loss was made with the transformers immersed in oil in copper cans to simulate actual operating conditions. The output transformer was placed in a can 4x6x7 in. and the interstage, in a can 4x3¾x3¾ in. The transformers were allowed to run for about an hour until approximately steady-state conditions prevailed. The final temperature for the output transformer was 64 C and for the interstage, 55 C. These temperatures were measured at the top of the oil, since thermocouple measurements indicate that this temperature is about the same as that of the core. Room temperature was about 30 C.

Chapter 3

ELECTRON TUBE DEVELOPMENT

3.1 INTRODUCTION

THE COUNTERMEASURES work done under Division 15 required considerable vacuum-tube development work, both in the design of new tubes and in the modification of existing ones. Most of this work was carried on by the General Electric Company (under contracts OEMsr-931 and 1019), the Westinghouse Research Laboratories (under contract OEMsr-747), the Federal Telecommunication Laboratories, Inc. (under contract OEMsr-1034 and 1430), the Bell Telephone Laboratories, Inc. (under contract OEMsr-1222), the Litton Engineering Laboratories (under contract OEMsr-1357), the Radio Corporation of America (under contract OEMsr-1043), the Radio Research Laboratory, Harvard University (under contract OEMsr-411), and Sylvania Electric Products, Inc. (under contract OEMsr-1456).

The work under these various contracts is summarized in this chapter. A theoretical study of magnetrons is discussed in Section 6.4.1.

The majority of the tubes developed are described in detail in an RRL monograph.[809] A discussion is given there, also, of the principles and methods of operation of these tubes and of their applications and the circuits in which they are used. For this reason, the discussion that follows is limited to a brief outline of how the tube development progressed, together with tables listing the tubes and their principal characteristics.

All the tubes considered in this chapter went through considerable development. A large number of other experimental tube types were investigated and partially tested, and then dropped, either because of technical difficulties or because of lack of interest on the part of the National Defense Research Committee [NDRC] and/or the Armed Services.

3.2 LOW- AND MEDIUM-POWER TUBES

Several low-power tubes were developed, including magnetrons and other types, with powers of less than 100 w. In addition, a considerable number of medium-power magnetrons were designed, with powers ranging from 100 w to 300 w, but mostly about 150 w.

3.2.1 Low-Power Tubes

The tubes which were developed with powers below 100 w included squirrel-cage magnetrons, tubes for use in local oscillators and similar applications, and parallel-plane triodes and tetrodes. The more important ones made by the General Electric Company under Contract OEMsr-931 and by the Sylvania Electric Products Company are listed in Part A of Table 1. In the same table in Part B are listed medium-power tubes also made by the General Electric Company and by the Radio Corporation of America; these are discussed at greater length in Section 3.2.2, page 42.

Low-Power Squirrel-Cage Magnetrons

A project was carried out jointly by Radio Research Laboratory [RRL] and Sylvania Electric Products, Inc., with the assistance of the Radiation Laboratory [RL], Massachusetts Institute of Technology (under Division 14), for the development and testing of a low-power squirrel-cage type of magnetron for use at S-band frequencies (10-cm region).[487, 685]

A considerable amount of work was done in determining the mechanism of operation of these tubes. A number of modes of operation were discovered by use of cold-test measurements and were verified with hot-test measurements. The ratio of air gap to copper thickness in assembled anodes, the ratio of anode diameter to finger length, and the size and shape of the end cap were all studied as parameters affecting the operation of the tube.[750]

The equipment used at RRL in these tests was finally transferred to Sylvania Electric Products, where it was expected that the project would be continued by direct Service contract.

TABLE 1. Characteristics of low-power and medium-power electron tubes.

Tube devel. no.	RMA no.	Contractor and contract no.*	Div. 15 proj. no.	Tube type†	Approx. freq. range (mc)	Approx. c-w output (w)	Approx. eff. (%)	Magnetic field (gauss)	Max. anode potential‡ (kv)	Max. anode current (amp)	Type of output§	Status‖ at end of World War II	References	Remarks
					A. Low-power tubes.									
ZP-633		GE-931	RP-244A, 430A	S.A.Mag.	300–1,500	25–10		3,300	1.2	0.1	P.L.	I	Section 3.2.2.	Double-ended. Similar to ZP-646. Discontinued.
ZP-652		GE-931	RP-430A	Mag.	1,000–3,000	25					Coax.	I		Discontinued.
L-14		GE-931	RP-396, 430A	P.P. Tri.	1,500–3,000	20–10	10		1+		Coax.	III	135	Discontinued.
X-6041		Sylv.	RP-430B	Mag.	3,500–5,500	50		2,000	1.2		Coax.	I		
					B. Medium-power tubes (Flute project).									
ZP-590	5J30	GE-931	RP-244A	S.A.Mag.	10–375	150	25–55–40	1,500	2.5	0.40	P.L.	IV		
ZP-646	5J32	GE-931	RP-244A	S.A.Mag.	90–450	150	30–50–30	1,500	2.5	0.40	P.L.	IV		Double-ended.
ZP-666		GE-931	RP-244A	S.A.Mag.	120–230	150	40	1,500	2.0	0.40	P.L.	III		Production completed. Similar to ZP-590.
ZP-579	5J29	GE-931	RP-244A	S.A.Mag.	350–770	150	40–20	1,500	2.5	0.40	P.L.	IV	129	
ZP-675		GE-931	RP-244A	N.Mag.	425–775	150	50	1,500	2.5	0.40	P.L.	II		To replace ZP-579.
ZP-584	5J31	GE-931	RP-244A	S.A.Mag.	700–1,200	150		2,600	2.5	0.40	P.L.			Similar to ZP-579.
ZP-676	5J33	GE-931	RP-244A	N.Mag.	750–1,150	150	50–35	1,500	2.5	0.40	P.L.	III		Replaced ZP-584.
ZP-677		GE-931	RP-244A	N.Mag.	1,100–1,650	300	50–35	1,500	2.5	0.40	P.L.	I		
A-131		RCA-1043	RP-244B		8,500–10,300	100–200			2.0		W.G.	II	290, 291, 292, 294, 295	

*Contractors and contract numbers:
GE-931 = General Electric Company; OEMsr-931.
RCA-1043 = Radio Corp. of America; OEMsr-1043.
Sylv. = Sylvania Electric Products Company.

†Tube types:
Mag-Magnetron
P.P.Tri = Parallel-plane triode.
S.A.Mag. = Split-anode magnetron.
N. Mag. = Neutrode magnetron.

‡In general, anode voltage and current should not simultaneously be a maximum.

§Type of output:
P.L. = Parallel line.
Coax. = Coaxial line.
W.G. = Wave guide.

‖Status:
I = First research stage.
II = Concluding research stage.
III = Preproduction stage.
IV = Factory production stage.

LOCAL OSCILLATOR TUBES

A project was initiated to explore the possibilities of developing local oscillator tubes capable of operating over a very wide frequency range. A tuning range of from 3,000 to 10,000 mc with an output power sufficient to operate a crystal mixer was required. Ease of manufacture and mechanical ruggedness were important requirements. Two tubes, the 2K48 and the 2K49, were developed by Bell Telephone Laboratories, Inc., and approximately 90 tubes were supplied to RRL for comments and for use in developing receivers.[309]

Description of Tubes. The 2K48 and 2K49 vacuum tubes were velocity-variation tubes of the reflex type employing focused electron beams. They required external cavities in the form of a tunable coaxial line, the center conductor of which forms an integral part of the tube as supplied. Tuning was achieved by an adjustable piston which varied the effective length of the coaxial line. This piston could be of the positive-contact type or it could employ resonant chokes. The tubes required two d-c voltages in addition to the normal heater sup-

ply, one being a fixed potential of either 1,000 or 1,250 v and the other being adjustable between 0 and 500 v, the exact value varying with the operating frequency. The two tubes were externally identical; differing only in internal design to permit best operation over different portions of the desired frequency range.

The electrically significant details of these tubes are an electron gun which directs the electron beam through a high-frequency aperture or gap, two copper disks containing holes which define this gap, and a repeller electrode which produces a reflecting and focusing field to redirect the electron beam through the h-f gap after a critically valued time of transit in the reflex region. The determination of the optimum shape and size of these electrodes and the mechanical problems associated with their construction and assembly to the required tolerances formed a major part of the development work.[310]

Special Problems. A number of rather special problems were encountered in the design of a wide tuning range reflex oscillator which are not present in the usual reflex tube.

In the first place, the efficiency with which the r-f gap performs its function is dependent upon the length and diameter of the gap and upon the beam velocity as these are related to the operating frequency, so that a compromise design was necessary.

The electron transit time in the reflex region is critically valued and dependent upon the operating frequency. It could be controlled by the potential of the repeller; but the repeller field must also focus the reflected beam on the gap, and this requires a definite repeller potential conflicting with the transit time requirements. Another compromise is necessary.

Then there exists a number of discrete regions of the repeller potential for which oscillations at any specified frequency can be obtained. These regions, designated as repeller modes, correspond to electron transit times in the repeller field centering around values given by $\theta = N + \frac{3}{4}$, where θ is the number of complete cycles at the operating frequency corresponding to the transit time and N is any integer. Only certain of these modes can operate with sufficient power to be useful, and the frequency ranges of these vary. The most useful tube is one in which one mode is particularly strong and persists over the entire frequency range to be covered.

The situation is further complicated by the fact that there are a multiplicity of different frequencies at which any given cavity will oscillate with a fixed tuning adjustment. These different frequencies lie in different ranges which, for the coaxial line cavity, correspond to lengths of one-quarter, three-quarter, five-quarter wavelengths, etc. Only the first two of these ranges are useful, but operation on any others interferes with the use of the tube. The principal problem in the construction of a wide-range reflex oscillator is, therefore, related to the proper distribution of the repeller modes and of the cavity ranges, so that unfortunate combinations of these do not give overlapping operating regions.

Finally, the returned electrons must not be allowed to re-enter the gun region or an undesirable hysteresis effect is produced. This effect is manifested by a shift in repeller voltage required for operation depending upon the direction from which this range is approached. In the 2K48 and the 2K49, this effect was minimized by the use of a different hole size in the two gap electrodes.

Parallel-Plane Triodes and Tetrodes

The L-14 was a modified version of the ZP-572 (RMA No. 2C39) lighthouse triode or so-called oilcan tube and was redesigned for use at high frequencies in the Peter system (see Section 13.3.1). Three important changes were made in the ZP-572 structure: (1) The mesh grid of the ZP-572 was replaced by a parallel-wire grid in which each wire is mounted under tension; (2) the grid-cathode spacing was reduced from 0.004 in. to 0.002 in.; and (3) the improved transconductance due to the reduction of the grid-cathode spacing permitted an increase in the grid-anode spacing from 0.020 in. to 0.045 in. Bench tests showed that these changes improved the operation.[135] (See part A of Table 1.)

The L-14 has found extensive use in the Peter system as an amplifier, both in the 500- to 700-mc range and in the 3,000-mc range. A further variation of the L-14 was built for operation at 2,000-v anode voltage instead of the

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1,000-v anode potential which is now used.

Lower-Frequency Versions. A preliminary investigation was carried out on the practicability of scaling the parallel-plane lighthouse tube geometry up to achieve high power in the frequency range between 100 and 350 mc. Several triodes (L-200 type) and tetrodes (L-201 type) were designed for operation at voltages up to 5,000 v and currents up to 2 amp. The triode was scaled from the ZP-464 (RMA No. 2C43). This project was dropped at an early stage because of low radio countermeasures [RCM] interest and increased pressure on other projects; but sufficient experience was gained to make it fairly clear that the problems involved in scaling the lighthouse structure to high power are soluble and that the power output predicted by the scaling formulas can probably be realized.

3.2.2 Medium-Power Magnetrons

Enemy radar was concentrated, for the most part, in the range between 100 and 1,000 mc, over most of which no standard tubes existed capable of generating high continuous power for jamming. It was therefore necessary to carry on a program of tube development in this range, known as the Flute project. At the same time efforts were made to extend the frequency range upward to cover other possible enemy radar developments. The tubes developed under the Flute project are summarized below. Part B of Table 1 gives the characteristics of the major types.

Split-Anode Magnetrons

It has been known for some time[844, 845] that split-anode magnetrons were capable of generating considerable power in this frequency range. During the period between the invention of the split-anode magnetron in 1924 and 1940, a number of difficulties were uncovered which prevented the acceptance of magnetrons for use in communications.

Drawbacks of Magnetrons. These traditional drawbacks were the subject of a comprehensive investigation by the General Electric Research Laboratories, with the result that great strides were made in the design of this type of tube. Some of these problems, and their solutions, which have been worked out under contract OEMsr-931, are as follows.

1. *Power limitations due to decreasing size at high frequencies.* A split-anode magnetron will not achieve an efficiency higher than 20 per cent or so at 1,000 mc unless the applied magnetic field is higher than 2,000 gauss. If the anode voltage is to remain below 3,000 v, the anode diameter must be so small that it is impossible to dissipate large quantities of power by radiation or lead conduction. This problem was solved by the introduction of liquid cooling.

2. *Filament back heating.* Except at frequencies so low that the transit time of electrons from cathode to anode is a very small fraction of 1 cycle, appreciable numbers of electrons return to the cathode with energy which they have picked up from the h-f fields. This problem has been dealt with in two ways: by making the cathodes of rugged tungsten wires or spirals and by liquid cooling (see also Section 6.5.3).

3. *Glass bombardment at low frequencies.* At frequencies below 150 mc or so in fields of the order of 1,500 gauss, electrons escape in large numbers from the anode and bombard the glass walls of the tube and the electrode seals. This problem was solved in two ways, in two of the l-f tubes. In one (ZP-590), electrically floating shields were mounted on the anode leads; in another (ZP-646), a complex system of shields across the anode gaps prevented the escape of the electrons.

4. *Modulation characteristics.* For amplitude modulation, the magnetron has two undesirable characteristics: the frequency does not remain constant with amplitude variation, and the output cannot be reduced continuously to zero. No good technique was evolved for dealing with either of these properties, but for jamming they are not detrimental. A little frequency modulation of the carrier improves the spectrum, whereas the nonoscillation at low voltages does not mar the spectrum, provided the modulator can drive the tube back into oscillation without an appreciable hiatus in time.

5. *Frequency limitations consistent with tunability.* For jamming applications it was highly

desirable that the oscillator be tunable over a wide frequency range. This is most easily achieved by having part of the oscillator tank circuit outside the tube, but at high frequencies the usual Lecher wire tank circuit is so short that no part of the tank could be brought outside of the vacuum. This difficulty has been overcome by the use of an extra internal loop, which forms a half-wave line combination with the external Lecher wire system.

Tube Types. Four main tube types were employed at medium levels of power (see Table 1).

1. *ZP-590 type.* The ZP-590 (RMA No. 5J30) operated nominally over a range from 175 to 375 mc; the lower limit of the frequency range, however, was set by the transmitter in which it was used. With a suitable external tank, the frequency could be run down indefinitely. The ZP-666 was a tube of the same type except that its anodes were loaded with extra-capacity plates to cover the frequency range 120 to 230 mc.

2. *ZP-579 type.* The ZP-579[129] (RMA No. 5J29) had essentially the same operating characteristics as the ZP-590. The ZP-584 (RMA No. 5J31) was of the same type except that it had a smaller internal loop and operated in a field of 2,600 gauss. Both of these tubes suffered from severe back heating of their filaments.

3. *ZP-646 type.* The ZP-646 (RMA No. 5J32) was of double-ended construction to permit the connection of short circuits or capacities across the extra pair of leads and thus extend the frequency range. Its operating characteristics were essentially the same as for the above tubes. The ZP-633 in principle was the same as the ZP-646 but was scaled down to operate (air-cooled) at 25- to 10-w output over the range 300 to 1,500 mc. It was contained in a stainless steel shell, with built-in magnet pole pieces, and tuned by symmetrically sliding shorts on two Lecher wire systems connected to the two pairs of anode leads. Satisfactory operating life was not achieved for this tube.

Future Work. Much remains to be done on tubes of this type. All of these tubes were designed and started for production on an accelerated schedule, so that the research program was restricted to work directly applicable to the operation of the tubes. It would be very desirable to develop a tube in a metal envelope with built-in pole pieces. Several unsolved problems related to envelope and seal bombardment by electrons, drop-off in efficiency during operation (apparently associated with the secondary electron emission properties of the anode faces), drop-out of oscillation at low levels, and so forth, still remain to challenge the magnetron designer.

High-Frequency Tunable Magnetron

The A-131 tunable magnetron was developed for use in airborne, X-band jammers.[292, 294, 295] A number of tubes were built, and a fairly uniform output over most of the tuning range was achieved, although one "hole" existed in the spectrum. Difficulties with cracks in the mica window seals were overcome by eliminating thermal shock during assembly.[290] Cathode studies indicated a possibility for simplifying constructional problems[291] (see Table 1).

Neutrode Magnetrons

It was discovered at the General Electric Research Laboratory that the addition of a third electrode to the split-anode magnetron structure permits the tube to operate as though it were a four-gap tube. Suitable variations of this geometry would allow operation equivalent to that with six, eight, or more gaps. Since the extra electrode is located in an electrically neutral plane and presumably operates at zero r-f potential, the tube was referred to as a "neutrode." Higher-order operation presented several important advantages: h-f operation was possible with low magnetic fields; filament back heating was materially decreased; and higher efficiencies were realized.

The basic tube of this type was the ZP-676. The tank circuit for this tube operated in a full-wave mode. The ZP-676 was to supersede the ZP-584 (see above). The ZP-675 is a lower-frequency tube of the same type, to supersede the ZP-579. The ZP-677 is another neutrode covering a higher frequency range (see Table 1). The ZP-647 and ZP-685, discussed in the following section, are also neutrode-type tubes (see Table 2).

TABLE 2. Characteristics of 1-kw magnetrons (Piccolo project tubes).

Tube devel. no.	Contractor and contract no.*	Div. 15 proj. no.	Tube type†	Approx. freq. range (mc)	Approx. c-w output (kw)	Approx. eff. (%)	Magnetic field (gauss)	Max. anode potential‡ (kv)	Max. anode current (amp)	Type of output§	Status‖ at end of World War II	References	Remarks
ZP-599	GE-931	RP-158F	S.A.Mag	90–260	1	40–55	1,750	2.5	1.0	P.L.	III	Section 3.2.2	Similar to ZP-590.
ZP-647	GE-931	RP-158F	N.Mag.	240–500		50	1,250	2.5	1.0	P.L.	IV		
ZP-685	GE-931	RP-158F	N.Mag.	450–660	1	50–55	1,500	2.5	1.0	P.L.	I		Turned over to RCA. Similar to ZP-676.
A-132	RCA-1043	RP-158D	M.A.M. (4)	400–700	1	60	1,500	2.5	1.0	P.L.	II	292, 296	Development completed. Modification of ZP-685.
A-133	RCA-1043	RP-158D	M.A.M. (6)	620–930	1	50	1,500	2.5	1.0	P.L.	II	292, 297	Development stopped.
ZP-594	GE-1019	RP-158A	M.A.M. (8)	460–640	1	50–60	900–1,650	4	0.5	Coax.	II	253, 491	Discontinued.
ZP-615	GE-1019 & FTR-1430	RP-158A, 158C	M.A.M. (10)	600–840	1	65	1,000–2,000	4	0.5	Coax.	I		Turned over to FTR.
ZP-616	GE-1019 & FTR-1430	RP-158A, 158C	M.A.M. (10)	760–1,160	2	50–75	1,500–2,650	5	0.5	Coax.	II	248, 339	Development completed, by FTR.
ZP-597	GE-1019	RP-158A	M.A.M. (12)	1,000–1,400	1	50–60	1,500–3,350	4	0.5	Coax.	III	250, 254	
ZP-838	Litt-1357	RP-158B	M.A.M. (12)	1,250–1,900	1	50	1,500	5	0.5	Coax.	I		Discontinued.
ZP-639	GE-1019 & Litt-1357	RP-158A, 158B	M.A.M. (12)	1,750–2,600	1	50–60	2,000–2,500	5	0.5	Coax.	II		Development completed.
ZP-612 (RMA:5J21)	GE-1019	RP-158A	M.A.M. (12)	2,600–3,350	1	50	2,200–3,200	5	0.5	W.G.	II	632	Turned over to Litton.
612L	Litt-1357	RP-158B	M.A.M. (12)	2,460–3,610	1	50–65	3,600	5	0.5	W.G.	III	337	Modification of ZP-612.
ZP-693	GE-1019 & Litt-1357	RP-158A, 158B	M.A.M. (12 or 16)	3,400–5,100	1	50	3,000–4,000	5	0.4	W.G.	I		Development stopped.
L-104	GE-1019 & Sylv.	RP-158A, 158C	M.A.M. (12)	6,950-10,400	0.5	35	5,000	5	0.4	W.G.	I	263	Discontinued.

*Contractors and contract numbers:
GE-931 = General Electric Company; OEMsr-931.
GE-1019 = General Electric Company; OEMsr-1019.
FTR-1430 = Federal Tele. & Radio Corp; OEMsr-1430.
Litt-1357 = Litton Engineering Labs; OEMsr-1357.
RCA-1043 = Radio Corp. of America; OEMsr-1043.
Sylv. = Sylvania Electric Products Company.

†Tube types:
S.A.Mag. = Split-anode magnetron.
M.A.M. (*N*) = Multianode magnetron (*N* elements).

‡In general, anode voltage and current should not simultaneously be a maximum.

§Type of output:
P.L. = Parallel line.
Coax. = Coaxial line.
W.G. = Wave guide.

‖Status:
I = First research stage.
II = Concluding research stage.
III = Preproduction stage.
IV = Factory production stage.

3.3 ONE-KILOWATT MAGNETRONS

In April 1943, a program known as the Piccolo project was begun at General Electric Company with the aim of developing a line of magnetrons for jamming purposes, as a countermeasure to the German radar systems then in use and as preparation against future enemy developments in the radar field.

The tubes were to generate continuous wave and were to cover the frequency range 500 to 10,000 mc at a power level which was not completely specified but which was to be of the order of 0.25 to 1 kw. They were to be capable

of modulation over a bandwidth of about 10 mc, and, since the complete frequency range was to be covered continuously, each tube had to be tunable over as wide a range as possible. Originally, the airborne use of Piccolos was foremost, with the consequence that 2 kv was set as the upper practical limit of the voltage.

Throughout the program, the emphasis was on speed of development rather than on perfection. For this reason, it was decided that, except in special cases, redesign of early tubes would not be undertaken in the light of later experience. As far as possible the program was kept unified, so that there would be as much resemblance as was practicable between different tubes, with the object of simplifying the apparatus problem. The tube characteristics are summarized in Table 2.

3.3.1 Redesign of Flute Tubes

At the start of the program, the two-anode and neutrode types of magnetrons were already under development in the Flute project (see Section 3.2.2) for medium powers. It was decided, therefore, that an attempt should be made to redesign these tubes to operate at the higher powers required.

It was found relatively easy to increase the power output of the medium-power types of split-anode and neutrode magnetrons to 1 kw, without changing the external dimensions of the tube. This was accomplished by the use of heavy-spiral filament cathodes, larger anode blocks, and more complete shielding to prevent electron bombardment of the glass. These changes generally increased the anode-to-anode capacity and loaded the tank circuit so that with the usual transmission-line circuit the frequency range covered with a single tube was not so great as the range covered by the equivalent Flute tubes.

Four basic tube types were thus developed for the 1-kw level. These tubes, whose characteristics are listed in Table 2, were as follows.

1. *ZP-590 type.* The ZP-599 was a 1-kw tube of the ZP-590 type. It covered the range 90 to 260 mc at voltages up to 2,500 and currents of 1 amp, in a magnetic field of 1,750 gauss.

2. *ZP-647 type.* The ZP-647 was a neutrode redesigned for the frequency range 240 to 500 mc, which it covered at voltages up to 2,500 v and currents of 1.0 amp in a magnetic field of 1,250 gauss.

3. *ZP-676 type.* The ZP-685 is a 1-kw tube of the ZP-676 type, covering the frequency range 450 to 660 mc at voltages up to 2,500 v and currents of 1.0 amp in a magnetic field of 1,500 gauss. The design of this tube was later changed from a neutrode to a true four-pole anode structure; it was then known as the A-132. This change increased both the efficiency and the frequency range.[292, 296]

4. *A-133 type.* The A-133 was a six-pole multianode magnetron, similar to the A-132 but covering the frequency range 620 to 930 mc. One operable tube for this range was produced.[292, 297]

3.3.2 Development of Multianode Magnetrons

There were several considerations which led to the development of a series of multianode magnetrons in addition to the redesigned Flute types. It would have been necessary, at the higher frequencies, to use the latter type in any case. A structure to operate at the long-wave limit of the range did not appear to be too cumbersome to be practical. Moreover, the Flute (two-anode) tubes were less efficient than could be expected for multianodes, and at the higher power level of Piccolos efficiency became more important.

In the development of the multianode tube, the experience of RL was available to draw on. The scaling technique held the hope that rapid adaptation could be made of their successful designs to the very different voltages, powers, and frequencies required in RCM.

Summary of Development

An outline of the development[251] is given below. The specific characteristics of the tubes can be found in Table 2.

Number of Tubes. The range 460 to 5,100 mc and 6,950 to 10,400 mc was covered by a total of nine tubes, eight in the former and one in the latter range. This represents an

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average ratio of 1.3:1 between successive tubes. The individual tube ranges themselves average 1.45:1, the lower-frequency tubes up to 1,400 mc averaging 1.40:1 and the higher-frequency ones up to 5,100 mc averaging 1.5:1.

Tube Type. Except for the ZP-616, all the tubes were of the radial-vane type (see Figure 1), double-strapped at one or both ends of the anodes. The radial-vane structure rather than the slot-and-hole was dictated by the need for a maximum of inductance and a minimum of nonvariable capacitance. (The ZP-616 was undertaken as a separate effort not coordinated with the main program.) Axially supported cathodes were used exclusively. They gave the advantages of symmetry, left one end of the cavity free for a symmetrical tuning arrangement, made rugged construction possible, simplified assembly, and did not interfere with the attainment of sufficiently uniform magnetic fields.

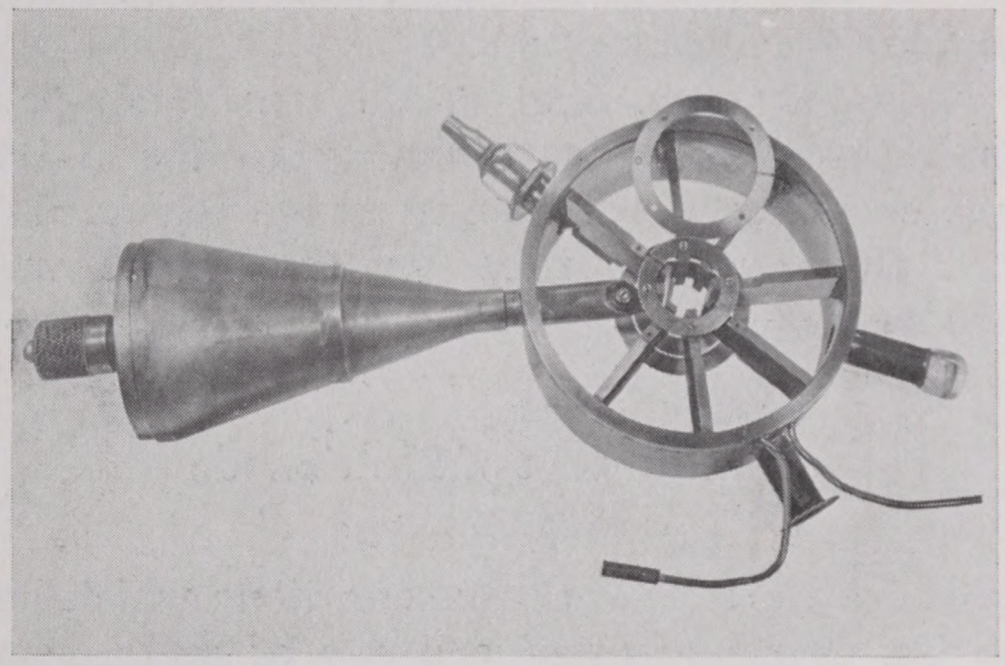


FIGURE 1. "Corny"-type tuner in experimental ZP-594 magnetron. This tube has vane anode, broken straps, and overvane loop output.

The tubes are essentially all-metal, except for the r-f output terminal.

Magnetic Field Design. With pierced pole pieces it was not difficult to design pole shapes which gave uniformity of field within ± 2 per cent over the interaction space, with a gap length not over 2.5 times the anode length and a pole diameter slightly less than gap length.[247] Less favorable geometry was often made necessary by space requirements of individual tube designs. In general, experience indicates that the fields were designed a good deal more conservatively than necessary.

Magnetron Output, 460 to 2,600 Mc. In this frequency range a loop coupler feeding out through a constant or variable impedance line was used. The loop which proved to be most satisfactory was of the overvane type (see Figure 1), which starts at the edge of a vane, extends a short distance parallel to the tube axis, then turns and extends radially outward to envelope (or casing), where it joins onto the inner conductor of the coaxial section of the output. The size of the loop determines the general level of the tube loading which is expressed as the external Q. Several other types of loops and other outputs were tried and discarded as being less satisfactory than this.

Magnetron Output, above 2,380 Mc. Here a wave-guide output was used. The design is entirely new. In essence it makes use of the principle of the dumbbell cross-section wave guide, in order to maintain cutoff wavelength and decrease impedance in making the transition from the large rectangular guide used for transmission to the much smaller cross section which can be arranged to couple power out of the magnetron cavity. In the ZP-612, the shell of this wave-guide transformer tapers from the rectangular cross section of the standard guide to a 1-in. diameter circle just before it joins the magnetron cavity wall (see Figure 2). In the same length two coplanar metal vanes extend inward from opposite sides of the shell, their opposing edges starting from the full guide-width separation and approaching to a separation of a few mils where they reach the inside of the cavity at the roots of the vanes. This close approach forms a slot and adds capacitive loading to the line. The slot is placed midway between two adjacent vanes from between which, but inside the output shell, a considerable portion of the casing wall has been removed so that current flowing from the root of one vane to the other cannot flow over the casing wall but encounters the impedance presented by the slot.

Tuning Methods. Four tuning methods were tried, of which one (with modifications in several cases) was universally adopted.

One discarded scheme was the use of Mumbo. This was a section of coaxial line closed at one end, the other end of the inner conductor being

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terminated in a flat plate which formed a variable condenser with a flat flexible end cover on the outer conductor. The end cover was manipulated through the rigid vacuum envelope

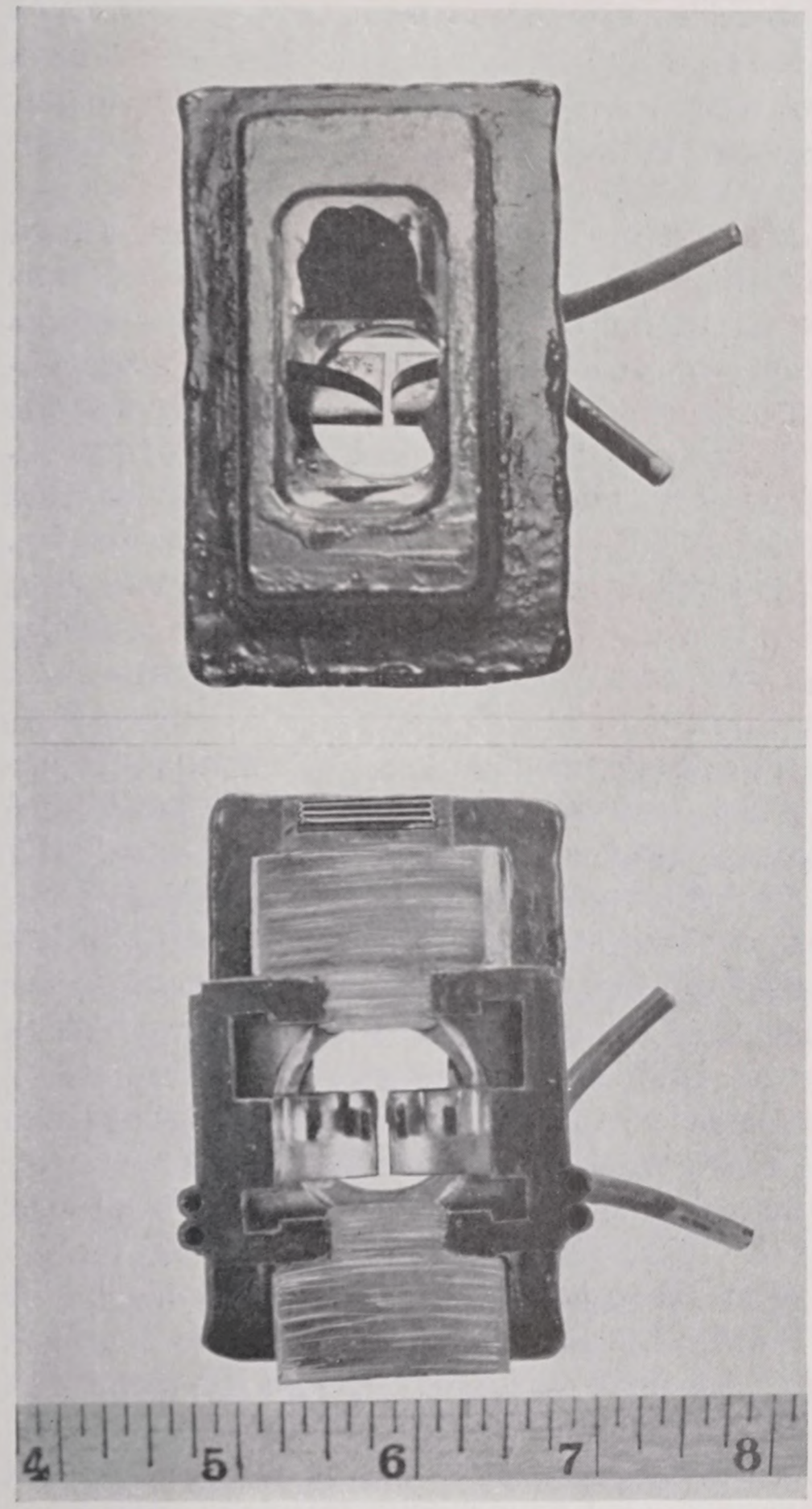


FIGURE 2. Early wave guide output for ZP-612 magnetron showing (*top*) outer end (from which the glass window has been broken out) with ramps leading back toward the anode, and (*bottom*) the inner end between roots of (cut-off) vanes at circumference of anode structure. (The output became inverted between pictures.)

by a metal bellows. This cavity was joined directly to the straps of the tank circuit by a section of low-impedance coaxial line which pierced the cavity's cylindrical side wall near the latter's closed end, the outer conductor joining the side wall and the inner conductor projecting in to join onto the inner conductor. Thus, Mumbo was effectively a step-up transformer which would convert small changes in susceptance at the variable condenser into large changes at the connecting line.

This could have been developed into a practical method. It suffered, however, from two disadvantages. The circulating energy in Mumbo, evidenced by marked heating, caused an additional power drain and the line-plus-Mumbo system had other modes besides the desired one so that the π mode of the cavity was no longer uniquely defined. The result was that three distinct modes of oscillation were found in operating a tube so equipped.

A third method which evolved out of the principle underlying Mumbo was to achieve the transformer action in a straight section of coax by expanding the outer conductor and contracting the inner conductor up to the termination in a variable condenser as before. This is shown in Figure 1. Here one of the vanes was cut down by the diameter of the outer conductor so that this conductor, projecting through the casing, replaced the cutaway portion of the vane. This was known as "Corny" because it looked like a cornucopia (and for no other reason). On cold test it showed two modes and a desirable tuning range. It, too, would suffer from additional power loss. It was never actually operated because "LC" was by that time well under way.

This last, "LC," was the generally useful tuning method. It arose from the combination of two separate methods, the variation of the effective capacitance of the tank circuit on the one hand and the variation of the effective inductance on the other. The capacitance was changed by using coplanar straps which had been widened radially and opposing them with a copper disk or ring, called the C-Ring, which was movable toward and away from them (see Figure 3). This was modified in the ZP-612 by not using the straps but by getting the capacitance with a system of fingers reaching in between the vanes near their tips. The ZP-639 embodies the same scheme.

The variation of inductance was achieved by

affecting the cross section available to the r-f magnetic field in its path through each sector and around the edge of each vane into the adjacent sector. A plain annulus, called the L-Ring, parallel to the plane of the anode, which when brought close to the vanes choked the field through the outer two-thirds of each sector was the earliest form tried. This was modified by adding extensions of various depth which reach into each sector until, in the L-104, the annulus disappeared and the arrangement

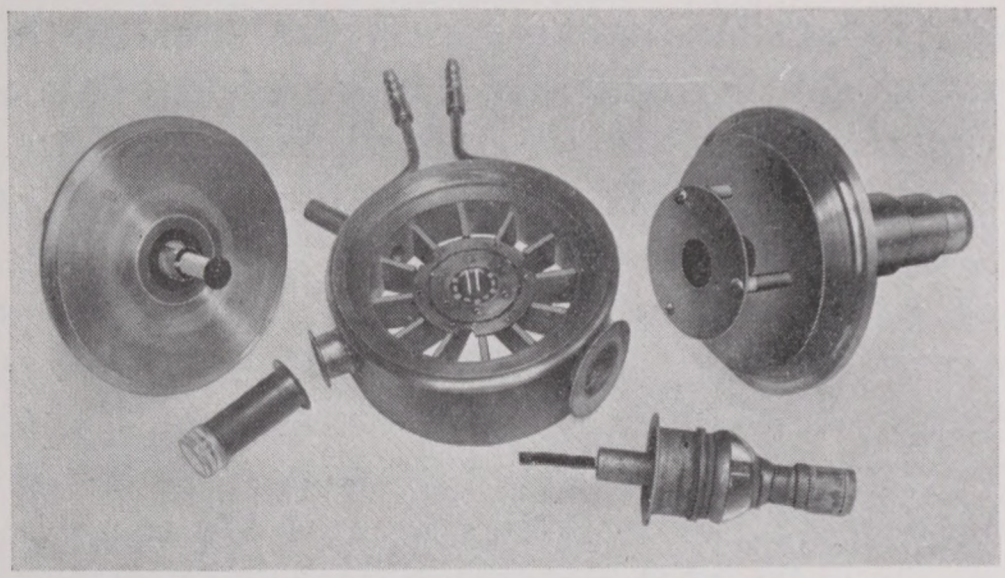


FIGURE 3. ZP597 magnetron disassembled showing cathode header with oxide-coated cathode, tank circuit with wide straps, and tuning header with "LC" tuner, L-Ring being next to header. Visual window and output with unformed loop are also shown.

is a "crown of thorns" adapted to the vane structure.

"LC" consists in having these two tuning methods operate simultaneously. Generally, this was accomplished by assigning one face of the anode structure to the C-tuning, placing the C-Ring there, assigning the other face to the L-tuning with the L-Ring there, and connecting the two together rigidly by metallic rods extending through the middle of three or more of the sectors. The exceptions are the L-104, in which L-tuning only is used, and the ZP-616, in which the different anode structure permits a single annulus to perform both L- and C-tuning functions.

Cathode. The nickel mesh oxide-coated cathode was usable in the ZP-594 and ZP-597 when they were used at the 2-kv rating. Their use was, however, attended by the need of rather extreme precautions to keep the end hats cool so that they would not emit even after being sensitized by the barium which inevitably got strewed around the tube after it had been run for some time.

Tests of secondary emitters were unsuccessful. At 2 kv, temporary operation was obtained with one or two such sources, but these invariably failed after short periods of operation. At 5 kv, slightly better performance was obtained, but it was not of a grade to warrant further experimentation in view of the availability of hot emitters.

Most of the ZP-612's which were made used a cathode of overwound tungsten coated with thoria wound on a thoria cylinder. The switch from the oxide-coated cathode was made because the higher operating temperature made the thoria-coated cathode better able to withstand the more concentrated back heating which resulted from the smaller cathode size. This cathode suffered from the difficulty that at operating temperature the thoria cylinder became sufficiently conductive to short-circuit and burn out.

The development of the Flute series of magnetrons and the independent work on ZP-616 showed that the simple geometry of the cylinder was not a requisite of a satisfactory cathode. Among those tubes are many with helical tungsten wire filamentary cathodes. Also, the change of tube voltage to 5 kv made it doubtful, on the basis of previous experience with other types of vacuum tubes, that the oxide-coated cathodes would stand up. This led to the adoption of helical tungsten filaments for a number of the tubes (in the range 460 to 1,400 mc).

For the smaller cathodes required in the ZP-612, it was determined that the requisite emission can only be furnished if the properties of thoriated tungsten are taken advantage of. Accordingly, this tube has a helical thoriated tungsten wire filamentary cathode.

Except for the L-104 all of the cathode helices are double-wound so that the current in adjacent turns flows antiparallel. In the ZP-612, where the turns are rather closely spaced, this is important for mechanical reasons. The magnetic repulsion of adjacent turns gives a stabilizing action against the approach of such turns toward each other. There is also an important electronic effect. The filament-heating current in a single helix produces a frequency

modulation (and at low powers an amplitude modulation) of the magnetron output. The current counterflow of the double helix greatly reduces this effect at the same time that the effect period becomes 120 c instead of 60 c for the usual 60-c a-c supply.

A complication in the structure of the cathode support, which has nothing to do with electron emission, has been found to be necessary in several cases. This is the use of a *quarter-wave choke* to keep power from flowing out of the cathode leads. The use of two wide straps necessarily of very different radii creates an unbalance in the resonant structure which excites the cathode with ultrahigh frequency. This is the case in the ZP-594, ZP-615, and ZP-597. In the latter tube, the choke creates a difficulty of its own by giving rise to a resonance at the short-wave end of its range.

The Multianode (Piccolo) Tubes. General information with regard to each Piccolo tube is contained in Table 2. In view of the foregoing discussion, this table is largely self-explanatory. There are, however, some comments to be made.

ZP-594 (see Figure 3) was the first tube to be developed. It and the L-104 are the only tubes with double-ring strapping at both ends of the anode. It has completely external pole pieces, insulators (quartz) in the LC tuning-rod structure, and multiple tuning knobs. The plan was to gang these mechanically. Work on it was suspended at the model shop stage because of the promise of tubes like the ZP-685 to put out 1 kw of power in essentially simpler tubes.

ZP-615 is an interpolation between the ZP-597 and the ZP-594. The LC tuning-rod structure is completely conducting.

ZP-616 represents a deviation from general family characteristics. Each spoke of the anode is made of a doubled-back piece of copper tubing, which is roughly L-shaped with the stem of the L radial and the tip of its base expanded into a rectangular loop. The base, extending into one side of the loop, forms an anode face. The strap connections start from a second side of the loop, thread through the next adjoining loop, and end on a third side of still the next loop. This is essentially "echelon" strapping. A single annulus serves for tuning. In its lowest position, it blocks the flux through the sectors formed by the stems of the L's and, in its highest position, it adds capacitance by its approach to flat pie-shaped lands brazed to the third side of the loops mentioned above. The annulus is fastened rigidly to the upper pole piece and this whole assembly moves axially in the tuning operation.

The effective water cooling of the anode faces allows this tube to be given a rating of 2.5-kw continuous output and necessitates more careful attention to the cooling of the output seal. Cooling is accomplished by an air blast projected against the inner edge of the seal from a series of oblique holes in the inner conductor.

ZP-597 was the second tube to be developed. ZP-638 was to be an interpolation between the ZP-639 and the ZP-597, probably lying closer to the 639 because that tube represents a much later stage in the general development.

ZP-639 is patterned to a large extent after the 612L. It is the last tube on a decreasing wavelength scale in which coax output is used. The 612L embodies many features which are different from its predecessors, namely, the broad-band wave-guide output transformer and 707 glass window, plunger C-Ring, tuning mechanism actuated by six tuning rods projecting through the magnetic pole outside the pole face proper, LC structure rigidly guided by 12 parallel tungsten rods sliding in copper inserts in pole pieces, thoriated cathode, and grounding of L-Ring to casing by tungsten spiral.

ZP-693 has been given no attention beyond debating whether to come out into standard S-band wave guide or nonstandard 1x2-in. inside diameter guide. Cathode requirements may dictate the use of 16 vanes.

L-104 has essentially crown-of-thorns tuning, with the thorns trapezoidal in shape to fit the 22½-degree sectors formed by the vanes. One thorn has been left out at the sector from which the output leads. Clearance between thorns and vanes and between thorns and the walls of their channels through the pole pieces is 0.005 in. The total length of thorn is about 0.62 in. and at the short-wave end of the tuning range the thorns extend through to the far side of

the anode, the length of which is 0.236 in. The tapered wave-guide output is terminated by a 0.003-in. to 0.004-in. thick mica window of full wave-guide cross section—no attempt has had to be made to adjust it for zero reflection at the center of the band.

General Recommendations. The one phenomenon which the Piccolo work served to emphasize and concerning which there is only slight empirical understanding is the *diode cutout.* This is a refusal of the tube to oscillate in the wanted mode. Whether the tube simply goes into a cutoff condition in which it passes (practically) zero anode current or jumps to another mode depends simply on the relation of the power-supply characteristic to the starting conditions for the other mode and the loading of that mode. It is doubtful that the loading of that mode has any effect on whether or not the original mode quits.

There appear to be two causes. One is overloading of the tube, in which case reducing the external Q either by using a different output transformer or by applying a suitable standing-wave ratio relieves the condition and permits the tube to resume normal oscillation. The other cause is a deficiency of electron emission, in which case increasing the supply by increasing the cathode temperature, for instance, is effective.

This phenomenon should certainly be investigated with the purpose of explaining its cause and mechanism.

Present Piccolos show *frequency shifts with envelope temperature and loading conditions.* Means of reducing this should be explored.

In extending the range of the series toward still higher frequencies there are the possibilities connected with basic shapes of *resonator structure other than the radial,* such as the cage type, the linear magnetron, and the neutrode type.

3.4 HIGH-POWER TUBES

Two general types of high-power tubes were investigated—magnetrons and resnatrons. Both types were found to be satisfactory for RCM use, although no large numbers of equipments using such tubes were built because of the specialized nature of their application and the relatively high cost of the tubes and associated equipment.

3.4.1 High-Power Magnetrons

At power levels above 1 kw, the techniques which have been described are no longer adequate for handling the anode dissipation and electronic envelope bombardment or, at high frequencies, for dissipating the power due to back bombardment of the cathode. Two entirely different tube types, the ZP-636 and the ZP-595, have been evolved for this power range and are described below.

ZP-636 Type Tube

This is a double-ended coaxial structure which covers the frequency range 85 to 350 mc by sliding shorts symmetrically placed in coaxial lines connected at the opposite ends of the tube. The cathode is a heavy tungsten spiral inserted through an arm which passes through the center of one pole of the magnet. This tube generates a power output which varies from 3,000 w at the center of the frequency range down to 1,000 w at the ends of the range. Its efficiency is about 50 per cent. It operates at voltages up to 4,000 v and currents up to 1.0 amp in a magnetic field of 2,000 gauss.

ZP-595 Type Tube

This is nominally a 10-kw tube and will cover a 15 per cent tuning range around a center frequency which can be set when the tube is designed, anywhere between 400 and 1,000 mc or so. Peak power outputs as high as 17 kw have been reached around 500 mc. Tuning is accomplished by motion, through a vacuum-tight bellows, of a plate which changes the capacity between the anode segments. The cathode is a water-cooled secondary emitter which takes the form of a copper bar coated with a magnesium alloy. A tungsten filament recessed into the cathode face provides enough

electrons to initiate oscillation. Returning high-energy electrons supply secondaries in sufficient numbers once oscillation is started. The ZP-595 operates in magnetic fields between 1,000 and 2,000 gauss, at plate voltages up to 20,000 and plate currents up to 1.5 amp. Its efficiency is of the order of 60 per cent.

A variation[25] of the ZP-595 has been worked out by the Westinghouse Research Laboratory. This tube is identical with the ZP-595 as far as its electrical design is concerned. Its tank circuit and tuning mechanism have been changed, however, to give it a wider tuning range and to permit it to operate into a wave guide instead of a coaxial line. A considerable number of these tubes have been made, including several variations of the fundamental design. The final models are sealed-off tubes, which employ Dowmetal-sprayed cathodes. These tubes have output seals which are specially treated to prevent fluorescence. Two tubes are required to cover the frequency range 350 to 700 mc.

The principal difficulty with the above tube is limited cathode life. Further improvement in elimination of fluorescence of the output seal and in coupling power out of the tube should also be made before the tube can be said to be entirely successful.

3.4.2 The Resnatron

Until very recently no tubes were available in the range of wavelengths from 300 to 1,500 mc which could deliver more than a few hundred watts continuously. In 1938, however, a new type of tube (called the resnatron) was invented which showed promise of becoming a good source in this range. In 1940, the tube had been developed to the point where it was interesting to NDRC and a development contract was let to the University of California by Division 14. The work was continued at the

TABLE 3. Characteristics of high-power magnetrons and resnatrons.

Tube devel. no.	Contractor and contract no.*	Div. 15 proj. no.	Tube type†	Approx. freq. range (mc)	Approx. c-w output (kw)	Approx. eff. (%)	Magnetic field (gauss)	Max. anode potential‡ (kv)	Max. anode current (amp)	Type of output§	Status‖ at end of World War II	References	Remarks
					High-Power Magnetrons								
ZP-636	GE-931	RP-116A	S.A.Mag.	85–375	1–3–1	50	2,000	4	1.0	Coax.	I		Double-ended. Discontinued.
Mod.¶ 34	West-747	RP-351A	S.A.Mag.	335–500	10	65	1,550	13	2.4	W.G.	II	23, 24	No production planned.
ZP-595	GE-931	RP-116A	S.A.Mag.	450–525**	10+**	60–65	1,000–2,000	14–20	1.3	Coax.	II	130	No production planned. Center frequency adjustable.**
Mod.¶ 36	West-747	RP-351A	S.A.Mag.	400–700	10	65	1,550			W.G.	I	23, 24	No production planned. Similar to Mod. 34.
					Resnatron								
Mod.¶ 21	West-747	RP-353A	Resn.	375–600	25+	75	.....	15	5.0	Coax.	III	25, 290	Demountable. Production completed

*Contractors and contract numbers:
GE-931 = General Electric Company; OEMsr-931.
West-747 = Westinghouse Research Labs.; OEMsr-747.

†Tube types:
S.A.Mag. = Split-anode magnetron.
Resn. = Resnatron.

‡In general, anode voltage and current should not simultaneously be a maximum.

§Type of output:
Coax. = Coaxial line.
W.G. = Wave guide.

‖Status:
I = First research stage.
II = Concluding research stage.
III = Preproduction stage.
IV = Factory production stage.

¶These were the numbers assigned to the final models. Earlier development models were given other numbers, as referred to in the text.

**The ZP-595 covers a 15 per cent frequency range about a central frequency determined by the design of the tube. It can be chosen anywhere between about 400 and 1,000 mc, and the power output depends upon this choice.

SECRET

Westinghouse Research Laboratories by Division 14 and was later transferred to Division 15, supported by OSRD Contract OEMsr-747. Tubes of this type were installed in operational ground barrage-jamming stations in the European Theater of Operations. This work has been reported in detail[23, 24] but a brief summary of the design features with be given in this volume.

As the operating frequency of vacuum tubes is increased, the transit time effects of the electrons become increasingly important so that a tube to be operated by grid control must have closer spacing of elements; but as the elements of the tube are decreased in size to obtain the closer spacing, the problem of dissipating heat generated by collision of the electrons with the different elements of the tube becomes serious. As the frequency is increased, there seems to be only one possible way of avoiding melting the electrodes, that is, by keeping the power output of the tube down. As a result, many tubes oscillating at high frequencies but giving little power have been designed. In a tube operating at very high frequency, it is impossible to avoid the effect of transit time. Rather than attempting to avoid this, the resnatron takes advantage of the transit time of electrons in such a way that larger spacings of the electrodes and lower voltages may be used. In this way adequate cooling of the various electrodes is made possible.

Another feature of the design is the focusing of the electrons in such a way that very few of them strike any electrode except the anode. Thus, the cooling problem of the intermediate electrodes is much reduced. Other features of the tube are that the tank circuit and grid circuit elements are connected directly to the electrodes without intermediate leads and are entirely inside the vacuum envelope surrounding the tube. This tends to make the tube large at long wavelengths. However, there are no external circuit elements involved except the output transmission line.

These fundamental principles of design have been incorporated into most of the various models of the resnatron which have been built. The first tube which gave large c-w power was a tetrode designed in 1940 and tested first at the University of California. In it were six pure tungsten filaments arranged so that the electrons traveled along the axis of the tube. It delivered 8-kw average power at 860 mc with an efficiency of almost 50 per cent. This operation was very encouraging and the testing of the tube was transferred during the summer of 1941 to the Westinghouse Research Laboratories, where a more adequate power supply and better facilities were made available for continuation of the development. The design and construction of the power supply took a year and the tests on the 860-mc tetrode were completed in the summer of 1942. This tube required a voltage of 20 kv on the second grid (called the accelerator grid) and 25 kv on the anode because of the large spacings in the tube. It was designed on a strictly experimental basis. The tube was demountable and included many rubber gaskets and was consequently extremely subject to vacuum leaks. However, the operation was sufficiently promising to warrant further development. The next tube which was developed was a triode for wavelengths of approximately 1,500 mc. It was not a successful tube because, although it oscillated and gave about 1-kw output, its efficiency was quite low. The next tube which was developed was a tunable tetrode for the wavelength range 475 to 500 mc for use in a ground barrage-jamming station as the countermeasure for the German night-fighter radar (see Chapter 11). This tube, with suitable later improvements, proved to be quite satisfactory for the purpose, and a considerable number were manufactured for operational use.

Development of a Sealed-off Resnatron

A project for the development of a special tetrode of the sealed-off type giving an r-f output power of 3 to 4 kw at 600 mc with an efficiency of 60 to 70 per cent was undertaken by the Federal Telephone and Radio Corporation. This tetrode was supposed to be scaled down from the higher-power tube described above.

A large number of tetrodes were constructed and tested[289] without reaching the desired results (the highest efficiency obtained at 600

mc was 30 per cent). After considerable studies and measurements of all the effects involved, the following conclusions were reached.

1. Geometric scaling probably cannot be applied to this problem because such scaling does not take into account the secondary emission of the anode.

2. The secondary electrons present in the screen-grid anode space may have a considerable effect on the behavior of the tube, even though they do not reach the screen grid, by absorbing energy from the r-f field.

3. The methods for suppressing secondary electrons used at lower frequencies, such as formation of virtual cathodes or introduction of a third grid, are probably not adapted to ultra-high frequency, where the transit time in the screen-grid anode space has to be considered.

4. The early theories of operation of the resnatron were probably not satisfactory. The success of the resnatron can probably be accredited to the high voltage used, which minimizes all transit time effects and eliminates secondary emission and to the extremely efficient cooling, which allows very high dissipations per unit area.

5. The development was terminated before all methods of suppressing secondary emission had been fully investigated. Additional development work in this field is certainly warranted.

Chapter 4

ANTENNAS AND RADIO-FREQUENCY POWER TRANSMISSION

4.1 INTRODUCTION

THE EFFECTIVENESS of any transmitter is greatly dependent upon the efficiency with which the associated antenna system radiates the output power of the transmitter. Transmitters used for jamming never have so great an amount of power available that any appreciable loss due to an inefficient radiating system can be tolerated. This is particularly true for radar jamming, since, as is pointed out in Chapter 11, the closer the target is to the radar, the more jamming power is required to screen the target effectively.

An efficient antenna system is likewise essential if the full capabilities of search receivers are to be realized. Except for direction-finding [DF] antennas, requirements are not so stringent, however, as for transmitters. Nevertheless, good reception requires an antenna system that is designed for the particular application. This is especially the case where a simple but not highly sensitive receiver is involved.

Similar considerations apply to the problem of r-f power transmission, since the efficiency of the overall system depends not only on the antenna and the transmitter or receiver but also on the means used to connect the two.

Most of the work described in this chapter on antennas and power transmission for radar countermeasures was done by the Radio Research Laboratory (under contract OEMsr-411). Most of the work on nonradar countermeasures was done by the Ohio State University Research Foundation (under contracts OEMsr-759 and NDCrc-100), the Radio Corporation of America (under contract OEMsr-895), and the Airborne Instruments Laboratory (under contract OEMsr-1305). The design considerations for all countermeasures antennas are discussed in the following sections; the actual antennas developed for radar countermeasures and nonradar countermeasures are then discussed in separate sections. This division of the discussion on actual antennas into nonradar and radar applications is made largely not for technical reasons but because of the fairly sharp division maintained within Division 15 between these two types of work: laboratories working on communications and other nonradar countermeasures (together with associated antennas) did but little work on radar countermeasures (and associated antennas) and vice versa.

4.2 DESIGN CONSIDERATIONS

Factors which must be considered in the design of antennas for radio countermeasures [RCM] include bandwidth requirements, directional characteristics, polarization requirements, and installation problems.

4.2.1 Antenna Bandwidth

Where operation is to be undertaken on a single frequency, or over a very narrow band of frequencies, the design of a transmitting or receiving antenna is not very difficult. Unfortunately, in RCM work a wide band of frequencies is almost always involved. Since the enemy communications or radar signals may appear on any frequency, it is desirable that each jamming transmitter have an antenna that will radiate efficiently over the entire frequency range of the transmitter.

This is particularly desirable in airborne applications, where it is generally impracticable (except with trailing-wire antennas) to make any changes in the antenna while in flight and where it is difficult, because of aerodynamic considerations, to modify an existing antenna even at a maintenance depot.

In practice, it is often found that the band of frequencies over which a transmitter is capable of being tuned cannot be conveniently covered by a single antenna structure. Under these circumstances the best compromise is to install an antenna that efficiently covers the known band of enemy frequencies and to replace or modify this antenna if operations in a new band of enemy frequencies must be undertaken.

SECRET

Practical antennas for airborne applications cover frequency ranges varying from as little as 1 per cent of the operating frequency to as much as two octaves in total bandwidth, e.g., a 200- to 800-mc antenna covers two octaves: one from 200 to 400 mc and another from 400 to 800 mc. Antennas for search receivers, on the other hand, are available for operation over bands in excess of 3 octaves, e.g., from 300 to over 2,400 mc. The wider frequency range for receiving antennas is the result of less stringent impedance requirements for receiving antennas.

In general, as the diameter of an antenna increases (its length remaining fixed), the band of frequencies over which it is capable of operating increases. For this reason, all wide-band antennas have a relatively large cross section and, when intended for airborne applications, often present mechanical design problems, particularly as regards the method of mounting. Conversely, the configuration of the mount may greatly influence the electrical operating characteristics of the antenna. For these reasons it is important that wide-band antennas be installed without modification of their mountings or housings.

Ground-based and ship-borne RCM installations frequently require less bandwidth than airborne applications, since it is often feasible to make the antenna adjustable or to employ several antennas for a given frequency range.

The above discussion of antenna bandwidth leads one to inquire just what is meant by the term bandwidth as applied to receiving and transmitting antennas. It has been found that most RCM transmitters will work very efficiently into a standing-wave ratio of 1.5 to 1 or less, and that most transmitters will operate satisfactorily into a standing-wave ratio of 2 to 1 or less. Receivers have been found to operate fairly satisfactorily into standing-wave ratios up to 5 to 1.

4.2.2 Antenna Directional Patterns

A very important consideration in the choice of an antenna or an antenna system is the manner in which the field strength of the radiated wave, or the response of a receiving antenna, depends upon direction. For some purposes it is desirable to confine the radiation in a very narrow beam; for others it is desirable that the antenna radiate or respond equally in all directions. The manner in which the radiated energy varies with direction is indicated by means of a "radiation pattern." Such a pattern is constructed by determining, theoretically or experimentally, the field strength at a constant distance from the antenna in various directions. Points are plotted whose directions from a common origin are the directions in which the radiation is measured and whose distances from the origin are proportional to the field strengths in these directions. The radiation pattern consists of the surface containing the points. The directional characteristics of a given antenna are, of course, the same for receiving as for transmitting.

When a highly directive antenna system is required, a number of antenna elements may be used, properly spaced and excited. Such a system of antennas is called an "antenna array." The high directivity of an antenna array results from the fact that the fields radiated by the various antennas that compose the array reinforce only in certain directions and cancel partly or totally in other directions. Directivity can also be increased by the use of reflectors, which may have a variety of shapes, such as a paraboloid, a V-shaped trough, etc. Still another type of directive radiator is the open end of a wave guide, preferably flared to form a horn.

In using airborne jamming transmitters against ground communications or radar installations, it is generally desirable for the airborne antenna to be nondirectional in azimuth but to have downward directivity in elevation. An antenna of this kind will radiate equally well toward all ground-based stations regardless of their azimuth and, in addition, all the power will be directed downward where it will be of the most value. Sometimes, however, it is desirable to have a pattern which has some gain in a forward direction, since the only stations of interest may be those ahead of the aircraft.

In antennas for ground-based or ship-borne

transmitters, on the other hand, directivity in azimuth is often of considerable value. By using directional antennas for this application, not only is it possible to direct the maximum amount of the available power toward the victim station, but also the possibility of interfering with one's own channels is minimized.

Antennas for ship-borne applications may require a relatively narrow beam in azimuth, to take advantage of the maximum gain compatible with accurate directional setting, but may require a fairly wide coverage in elevation, to compensate for the roll of the ship. It is always necessary, for a given application, to consider carefully the question of whether it is better to use the larger amount of jamming power required for this larger angle in elevation or to stabilize the antenna.

One precaution must be observed in using a directional antenna with ground-based jamming transmitters that are operating against enemy aircraft-interception [AI] radar or ground-to-air communications channels of ground-controlled-interception [GCI] systems. In both of these cases, jamming signals may be beamed along the path that is to be taken by the aircraft that are to be protected. However, if this beam is made extremely narrow in order to concentrate the maximum amount of power along the path, two adverse effects result.

1. The proposed course of flight is accurately defined for the enemy's benefit.

2. While staying outside of the beam the enemy might conceivably be directed close enough to the target to permit closing by visual observation.

Under these circumstances it is obviously prudent to sacrifice power concentration in the interest of not revealing one's plans in detail.

Broad-band directional systems in the h-f range present difficult antenna problems. In general, such antenna systems are designed as an integral part of the complete DF system. For this reason, no DF or homing antennas are described in this section as individual units. Instead, they are catalogued in Chapter 10. In passing, however, it should be pointed out that, although indications can generally be obtained from a DF system at frequencies outside of the band of operation for which the system is designed, these results are likely to be ambiguous. It is therefore important to use these systems only in the range of frequencies in which they are intended to operate.

4.2.3 Antenna Polarization

The radiation from simple dipoles, whips, and stubs is plane-polarized. In other words, the direction of the radiated electric field is parallel to the axis of the antenna. Such a field has maximum effect upon a receiving antenna when the latter is normal to the direction of propagation and parallel to the electric field, and zero effect when the receiving antenna is normal to the field. By special antenna design it is also possible to produce a circularly polarized field, for which the direction of the electric field at any point rotates at the radiated frequency. The receiving antenna then responds regardless of its orientation in a plane normal to the direction of propagation.

The importance of employing an antenna system whose plane of polarization corresponds to that of the enemy equipment cannot be overemphasized. If the victim receiver uses a vertical antenna, it is important that the jammer antenna also be oriented in the vertical plane. If this is not done, only that component of the radiated power corresponding to the vertical component of the radiated wave will be effective in jamming.

The choice between vertical and horizontal polarization involves more than just mounting a given antenna in one direction or the other. The questions of directivity patterns, relation of antenna to the ground plane, etc., are all involved. Consequently, it is desirable that the antenna system be designed for the intended service and that it be installed as originally contemplated. When the desired plane of polarization is not known or is mixed, the antenna may be mounted at a 45-degree angle, rather than either horizontally or vertically. If this is done, the antenna will radiate (or respond to) components in both planes, but with a loss in efficiency over that which could be obtained

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from an antenna mounted in the most favorable position for the wave being received.

Antennas having shapes other than that of an elongated cylinder, such as cones, for example, generally radiate (or receive) energy in various planes of polarization. The exact polarization of antennas of this type is complex and depends upon their specific configuration, their relation to the ground planes, and other factors. The advisability of tilting antennas of this type can best be determined from a study of the actual radiation pattern of the antenna involved.

4.2.4 Antenna Installation

The mechanical design of the antenna and its method of installation must always be such that it will withstand the severe service to which it will probably be exposed. Since all antennas of the type under discussion are for airborne, ship-borne, ground-based, mobile, or portable applications, the effect of wind, temperature, ice, vibration, and shock must be taken into consideration. In addition, for ship-borne antennas the effect of salt spray must also be considered. These mechanical design requirements, when combined with the electrical ones, often produce a difficult problem.

As a general rule, antenna installations should be made in such a way that, under normal operating conditions, an unobstructed "view" is had of the transmitter to be observed or of the receiver that is to be jammed. It is especially important to observe this precaution at the higher frequencies used for radar purposes.

In airborne applications, this requirement can generally be met by mounting the antenna on the underside of the fuselage. This location is not always practical, however, since the antenna may be too long for the clearance that exists when the airplane is on the ground. When warranted, retractable mounts may be used to overcome this handicap. As a second choice, the antenna may be mounted on the nose or on the side of the fuselage. Both of these locations have distinct disadvantages, however. In the former, the antenna is shielded towards the rear, in the latter, towards one side. Location of the antenna on top of the fuselage is particularly poor practice where jamming (or reception) of ground stations is involved, since the antenna is very likely to have predominantly upward directivity; however, this does not necessarily apply to relatively long antennas that may be supported between the tail and wings of the aircraft.

Ship-borne antennas must be installed in such positions that the superstructure of the vessel will not interfere with radiation patterns. It is generally necessary either to mount the antenna high enough so that no interference will be encountered or to mount two antennas, one on either side of the ship, and to use whichever one can be pointed in the correct direction.

An important consideration in the installation of any antenna is its position with respect to the metal surface that serves as a "ground" plane. Most airborne antennas are designed for mounting on the metal skin of an airplane and consequently will not perform properly if used without the metal ground plane. They cannot, for example, be located on the top of a mast nor can they be used on a nonmetallic airplane unless a metallic ground screen is provided. A conducting screen or netting, several wavelengths in extent, should prove entirely satisfactory for this purpose.

In considering the problem of providing an antenna that will respond to both horizontally and vertically polarized waves, it was suggested above that an antenna might be mounted at a 45-degree angle. It is to be noted that if an antenna designed for mounting on a metal surface is arbitrarily tilted with respect to that surface, the antenna characteristics are very likely to be considerably altered. Therefore, antennas that are to be mounted at an angle to a metal surface must be designed with this in mind. In some installations, as for example in some armored vehicles and aircraft, advantage may be taken of the contours of the vehicle to mount the antenna in the proper relation to the metal surface while still keeping it at an angle to the vertical and the horizontal. The proper tilt and relation to the metal surface may be attained in aircraft by mounting the

antenna part way up from the bottom of the fuselage. Some shielding then occurs, however.

4.2.5 Transmission Lines and Accessories

The installation of many antennas is such that a transmission line (which may be coaxial line, wave guide, or other type) is required between the transmitter and the antenna. It is important that the transmission line have adequate power-handling capacity and that it be of the impedance value for which the associated components have been designed. Since the impedance of the antenna is in general different from that of the line, some form of impedance-matching unit must be used. Although not always evident upon casual observation, impedance-matching units are built into the bases of many antennas in order to match them to standard-impedance transmission lines. In some installations, however, often in connection with broad-band antennas, technical limitations may require the use of transmission lines having other than standard-impedance values.

Care must be exercised in the selection and installation of antenna and transmission line fittings. At the very high frequencies even the best of these fittings introduce discontinuities into the circuit. Consequently only specified fittings can be used and no more should be installed than absolutely necessary. The same comments apply to r-f switches for these frequencies.

4.3 ANTENNAS FOR RADAR COUNTERMEASURES USE

The techniques employed in the development of antennas for radar countermeasures use have been thoroughly discussed in an RRL monograph,[809] so no further comment is necessary. The antennas which were carried through to the stage of building a prototype model, together with some of their characteristics, are shown in Table 1. A catalogue[599] is available which treats each of these antennas in some detail, giving a complete description, discussion of operation and installation, etc.

TABLE 1. Radar countermeasures antenna and transmission line developments.

Identification nos.	Description	Frequency range (mc)	References	Remarks
	Ship-Borne and Ground-Based Antennas			
RRL: F-3701 Div. 15: RP-138 Navy: AS-71/SPT-2	Dipoles and corner reflector.	450-720*	430	Tunable by adjusting lengths of dipoles.
RRL: F-3702 Div. 15: RP-138 Navy: AS-145/SPT-6	Dipole and corner reflector.	625-1,250*	818	Tunable by adjusting lengths of dipoles.
RRL: F-3903 Div. 15: RP-138	Dipole and corner reflector.	175-550*	819	Tunable by adjusting lengths of dipoles.
RRL: F-4700 Div. 15: RP-138 Army/Navy: AS-236/APT	Dipoles and corner reflector.	350-1,700*	820	Uses three interchangeable adjustable dipoles.
RRL: M-2906 Div. 15: RP-138 Navy: CAKZ-66/AKL	Dipole with corner reflector.	143-275*	708	
RRL: M-2907 Div. 15: RP-138 Navy: CAKZ-66/AKM CAPR-66/ALS	Dipole with corner reflector.	265-530*	708	

* Standing-wave ratio 2 to 1 or less.

SECRET

TABLE 1.—(*Continued*)

Identification nos.	Description	Frequency range (mc)	References	Remarks
RRL: M-2908 Div. 15: RP-138 Navy: CAKZ-66/ALT CAPR-66/ALT	Dipole with corner reflector.	445-820*	708	
RRL: M-2910 M-2913 Div. 15: RP-138 Navy: CAPR-66/ALU	Dipole with corner reflector.	810-1,385*	708	
RRL: M-2926 Div. 15: RP-138 Navy: CAPR-66/ALR	Dipole with corner reflector.	145-310*	708	
RRL: M-1201 Div. 15: RP-138 Navy: AS-37/SPT-4	Dipole and reflector.	340-400*		
RRL: M-2924 Div. 15: RP-138 Navy: CAPR-66/ALQ	Dipole and plane reflector.	88-174*		Dipole shortened by T loading element.
RRL: M-2901 Div. 15: RP-138 Navy: CAKZ-66/AJA	Sleeve dipole and reflector.	350-680*		
RRL: M-2902 Div. 15: RP-138 Navy: CAKZ-66/AJB	Sleeve dipole and reflector.	647-810*		
RRL: M-2903 Div. 15: RP-138 Navy: CAKZ-66/AJM	Sleeve dipole and reflector.	175-350*	493	
RRL: M-2904 Div. 15: RP-138 Navy: CAKZ-66/AJN	Sleeve dipole and reflector.	85-175*		
RRL: M-2909 Div. 15: RP-138 Navy: CAKZ-66/AJR	Horn.	790-1,420*		
RRL: M-2912 M-2915 Div. 15: RP-138	Horn.	1,375-2,440*		
RRL: M-2503 M-2504 M-2508 Div. 15: RP-279 Army: AS-49/TPT-1	Two dipoles and W reflector plus balun and transformer.	90-150*	434	For ground-based operation.
RRL: M-2509 M-2510 M-2511 Div. 15: RP-279 Army: AS-50/TPT-1	Two dipoles and W reflector plus balun and transformer.	150-210*	435	For ground-based operation.

* Standing-wave ratio 2 to 1 or less.

TABLE 1.—(*Continued*)

Identification nos.	Description	Frequency range (mc)	References	Remarks
RRL: M-2414 Div. 15: RP-138	Double cone.	900-3,000†		
RRL: M-2409 M-2410 Div. 15: RP-138 Navy: CU-19/SPR-1 AS-56/SPR-1	Double cone plus balun.	225-1,000†	405, 433	Furnishes coaxial input for search receivers.
RRL: M-2406 M-2408 Div. 15: RP-138 Navy: CU-19/SPR-1 AS-56/SPR-1	Balun and thick dipole.	75-300†	432	Furnishes coaxial input for search receivers.
	Airborne Antennas			
RRL: J-303 Div. 15: RP-138 Army/Navy: AS-33/APT-2	Thick stub.	460-775*		
RRL: M-313 M-318 Div. 15: RP-138 Army/Navy: AT-36/APT AT-41/APT AT-52/APT AS-114/APT	Thick stub.	165-230*	655, 443	Available with several types of mounting.
RRL: M-313 M-318 Div. 15: RP-138 Army/Navy: AT-37/APT AT-42/APT AT-53/APT	Thick stub.	120-175*	655, 443	Available with several types of mounting.
RRL: M-313 M-318, M-801 Div. 15: RP-138 Army/Navy: AT-38/APT AT-43/APT AT-54/APT AS-25/APR-2	Thick stub.	88-130* 70-400†	655, 443	Available with several types of mounting.
RRL: M-907 Div. 15: RP-138 Army/Navy: AS-36/APQ-2 AS-65/APQ-2 AS-116/APR-3 AS-117/APR-3	Thin stub (cut to length).	185-725*		Available with several types of mounting. Several stubs supplied which can be cut to various lengths to cover various parts of range.
RRL: M-1203 Div. 15: RP-138 Army/Navy: AS-67/APQ-2B	Very thick stub.	190-2,800*		Standing-wave ratio rises to 2.4 to 1 in range 1,700 to 1,850 mc. Patterns above 750 mc not satisfactory for many applications.

* Standing-wave ratio 2 to 1 or less.
† Standing-wave ratio 5 to 1 or less.

TABLE 1.—(*Continued*)

Identification nos.	Description	Frequency range (mc)	References	Remarks
RRL: M-4008 Div. 15: RP-303	Tapered stub with grounded sleeve.	88-175*	783	Streamlined for high-speed aircraft.
RRL: M-4011 M-4012, M-4013, M-4015 Div. 15: RP-303	Series of tapered stubs with grounded sleeves.	90-147* 134-257* 250-500* 500-935*	783	Series of streamlined stubs for high-speed aircraft. Interchangeable in single mount.
RRL: M-801 Div. 15: RP-138 Army/Navy: AS-26/APR-2	Cone.	215-3,000† 300-830*	444, 405	
RRL: M-801 Div. 15: RP-138 Army/Navy: AS-124/APR	Tilted cone.	270-1,000† 400-800*		
RRL: M-2101 M-2102, M-2103 Div. 15: RP-138 Army/Navy: AT-49A/APT AT-49/APR-4 AS-115/APT	Cone.	180-3,000† 290-2,500*	431, 443	Available with several types of mounting.
RRL: M-6000 Div. 15: RP-138	Tilted cone.	1,000-3,500†		Available with several types of mounting.
RRL: A-2612 Div. 15: RP-138 Army/Navy: AS-44/APR-5	Cone and high-pass filter.	1,000-3,500†	465	
RRL: A-2608 Div. 15: RP-138 Army/Navy: AS-125/APR	Tilted cone and high-pass filter.	1,000-3,500†	465	
RRL: M-2807 Div. 15: RP-303	Two stubs plus balun.	66-86†		Stubs have fineness ratio 0.25 for use on high-speed aircraft and are mounted tilted on side of plane.
RRL: M-2803 Div. 15: RP-303 Army/Navy: CU-64/APT	Stubs plus balun.	95-150*	821	Uses pair of AT-42/APT stubs or pair of AT-43/APT stubs (for different parts of frequency range) plus balun.
RRL: M-2804 Div. 15: RP-303 Army/Navy: CU-63/APT	Stubs plus balun.	150-210*	821	Uses pair of AT-41/APT stubs plus balun.
RRL: M-3203 M-3204 Div. 15: RP-303 Army/Navy: AS-181/AP	Set of balanced V sleeves.	195-675*	474	For horizontal polarization. Consists of one mount and three interchangeable antenna heads to cover range.
RRL: M-3211 Div. 15: RP-303	U-shaped sleeve dipole.	160-235*		Streamlined.

* Standing-wave ratio 2 to 1 or less.
† Standing-wave ratio 5 to 1 or less.

TABLE 1.—(*Continued*)

Identification nos.	Description	Frequency range (mc)	References	Remarks
RRL: M-3212 Div. 15: RP-303	U-shaped sleeve dipole.	176-245*		Streamlined.
RRL: M-3301 Div. 15: RP-303 Army/Navy: AS-108/APT	Split can.	575-1,400*	822	Horizontal polarization.
RRL: M-3302 Div. 15: RP-303	Split can.	650-1,850*		Horizontal polarization. Scaled model of above antenna.
RRL: M-2202 Div. 15: RP-303 Army/Navy: AS-69/APT CU-42/APT	Two crossed bent dipoles plus conversion unit.	530-580*	404	Circular polarization. When fed from two separate transmitters, may be used from 490 to 630 mc.
RRL: M-2203 Div. 15: RP-303	Two crossed bent sleeve dipoles.	500-700‡		Circular polarization.
RRL: M-2204 Div. 15: RP-303 Army/Navy: AS-251/AP	Two crossed bent sleeve dipoles.	440-660‡	823	Circular polarization.
RRL: M-2205 Div. 15: RP-303	Two crossed bent sleeve dipoles.	310-455‡		Circular polarization.
RRL: A-2702 Div. 15: RP-291 Army/Navy: AS-45/APR-6	Open-end wave guide.	3,000-6,000†	465	
RRL: M-4902 Div. 15: RP-303 Army/Navy: AS-259/AP	Horn.	2,070-4,140*	824	Contains built-in probe for output monitoring.
RRL: M-6806 Div. 15: RP-303	Slot.	1,050-2,100*	669, 760	
RRL: M-6807 Div. 15: RP-303 Army/Navy: AS-316/AP	Slot.	2,030-4,230*	669, 760	
RRL: M-6808 Div. 15: RP-303	Slot.	500-1,000*	760	
RRL: M-6809 Div. 15: RP-303	Slot.	395-646*	760	
RRL: M-6811 Div. 15: RP-303	Slot.	708-1,350*	760	
RRL: M-6812 Div. 15: RP-303	Slot.	1,240-2,430*	760	
RRL: M-7302 M-7305 Div. 15: RP-303	Curved slot.	500-1,000†	760	For mounting on leading edge of wing.
RRL: M-7304 M-7306 Div. 15: RP-303	Curved slot.	1,000-2,000†	760	For mounting on leading edge of wing.

* Standing-wave ratio 2 to 1 or less.
† Standing-wave ratio 5 to 1 or less.

SECRET

TABLE 1.—(*Continued*)

Identification nos.	Description	Frequency range (mc)	References	Remarks
		Antenna and Transmission Line Accessories		
RRL: M-2404 Div. 15: RP-138 Army/Navy: SA-14/APR-1	12-position r-f switch.	Up to 1,000‡	825	
RRL: M-2415 M-2413 Army/Navy: SA-44/APR	6-position r-f switch.	Up to 4,000‡	825	
RRL: M-2911 Div. 15: RP-138	R-f switch.	Up to 1,700‡		Motor-driven three-position switch.
RRL: M-2914 Div. 15: RP-138	R-f switch.	Up to 1,250‡	716	Single-pole double-throw r-f relay.
RRL: R-1000 Div. 15: RP-107	Wave-guide Y switch.	3,000-6,000*	495	
RRL: M-4601 Div. 15: RP-138	High-pass filter.	800 high-pass	611	
RRL: M-4602 Div. 15: RP-138	High-pass filter.	900 high-pass	611	
RRL: Z-2905 Z-2906 Div. 15: RP-286	Band-pass filter.	500-600		
RRL: Q-1911 Q-1912 Div. 15: RP-442	Band-pass filter.	2,200-3,500	666, 697, 613	
RRL: Q-1911 Q-1913 Div. 15: RP-442	Band-pass filter.	2,200-4,100	666, 697, 613	
RRL: Q-1928 Div. 15: RP-442	Set of filters.	Various bands in 1,000-5,000 range.		For use in identifying image and harmonic responses of search receivers.
RRL: R-1000 Div. 15: RP-107	Variable high-pass filter.	3,000-6,000	664	For use in identifying spurious responses in search receivers.
RRL: Q-1902 Q-1905 Div. 15: RP-442	Coaxial-line to wave-guide junction.	2,400-5,300	687	

* Standing-wave ratio 2 to 1 or less.
† Standing-wave ratio 5 to 1 or less.
‡ Standing-wave ratio 1.5 to 1 or less.

4.4 ANTENNAS FOR NONRADAR COUNTERMEASURES

A number of antennas and transmission lines have been developed for applications to nonradar countermeasures. Although the total number of such antennas is far less than the total number of the antennas developed for radar countermeasures purposes, there is, if anything, an even greater variety of types. A brief discussion of each general type will be given.

4.4.1 Developments for Ground-Based and Ship-Borne Equipments

Standard antenna design can generally be used for communications jamming purposes, especially from ground-based or ship-borne jammers. Some work has been found necessary, however, in modifications of the standard designs. These are usually of a specialized nature concerned with the problem at hand, and their solution uses standard techniques; hence, no discussion will be given here of such problems. The special problems deserve mention.

SECRET

Antenna System for AN/GRQ-1 Ground Jammer

It was learned from intelligence sources, before the V-2 rockets were actually launched, that they were to be provided with at least partial radio control. The AN/GRQ-1 ground jammer was available for countermeasures purposes, and it was found necessary to design special antennas which would cover all conceivable needs before the launchings were started. Eight antennas were designed for each transmitter in order to cover the frequency ranges 20 to 35 mc and 35 to 60 mc in two different general directions and two polarizations from ground locations in England. The vertically polarized antennas were of the terminated vertical half-rhombic type, whereas those for horizontal polarization were terminated full-rhombic antennas. The angular coverage of each antenna was about 30 degrees.

These antennas were later made portable for use on the European Continent.

Radio-Frequency Switches for Model "Tea" Jamming Equipment

A coaxial line switch[319] (Type CLU-24314) was developed to provide means for selectively connecting a coaxial input cable to any one of a number of coaxial antenna feeders. This switch was especially designed for ship-borne use with the Model Tea jamming transmitter. The switch has very good standing-wave ratio characteristics up to 900 mc and allows connection to any one of eight output coaxial lines, feeding antennas.

A revised model of the switch[328] has been constructed which gives satisfactory performance up to at least 1,500 mc.

The Wave Antenna

An investigation[99, 101, 105] was made of the possibility of using the standard Beverage-type wave antenna for countermeasures purposes. Initial tests indicated that the antenna might be of considerable value in the 100- to 200-kc range. The principal virtues of this antenna are the abolition of the requirement for high towers and the nonselective input impedance obtained. The principal disadvantage is that radiation in the direction of the conductor is obtained only at the cost of loss of energy in the soil.[a]

Because of the lack of efficiency involved, this antenna cannot be considered as a competitor to other directive systems consisting of arrays of elements having high radiation efficiency; however, the simplicity of such an antenna means that, for military purposes at least, it may offer worth-while advantages at frequencies up to 10 or 20 mc.

4.4.2 Antennas for Airborne Use

A number of airborne antennas have been designed for nonradar countermeasures use. Most of the designs were in the lower-frequency ranges, since standard radar countermeasures designs could generally be used elsewhere. Some antennas, however, were developed for higher-frequency ranges, especially for uses which required somewhat less bandwidth than provided by standard radar countermeasures antennas.

V-Antennas for Horizontal Polarization

A series of quarter-wave V-type dipoles were developed to give horizontal polarization with a reasonably uniform radiation pattern in the horizontal plane. A set of four antennas was developed for the frequency range 500 to 1,500 mc. Four more were designed for the range 1,500 to 3,000 mc. These antennas are interchangeable on a standard-type mounting base.

Trailing-Wire Antennas

The difficulty of mounting antennas on an aircraft fuselage for use in the upper-high-frequency and very-high-frequency bands without introducing serious pattern distortion caused by resonant and shielding effects of the nearby wings, tail, propeller, other antennas, etc., led to the development of antennas which can be removed from the immediate vicinity of the aircraft. A relatively broad-band (approximately 20 per cent) doublet antenna was designed which could be trailed behind the aircraft, using

[a] Radiation from this antenna (in the direction of the conductor) is due to refraction of the wave by the ground. The tilt of the electric vector depends upon the dielectric constant and resistivity of the ground as well as the frequency. There is no wave tilt over a perfect conductor.

a coaxial-feed cable as a tow line. When vertical polarization is desired, a 30-lb weight is employed at the end of the antenna to fly at approximately 45 degrees from the vertical. A small wind sock is used when horizontal polarization is desired, causing the antennas to fly within 10 degrees in the horizontal. This performance is for aircraft speeds of the order of 200 mph.

This type of antenna was investigated in the 20- to 50-mc range, over power-handling capabilities[94] up to 3 kw. Reports have been issued on design details[225] and on field tests.[234]

Sleeve-Type Antennas

Sleeve antennas are series-resonant antennas of the stub type having relatively small dimensions and impedance characteristics which, while not flat, are intrinsically broad-band. These antennas are so adjusted as to permit broad-band impedance matching by means of a simple series line-section transformer. The theory of such antennas is discussed elsewhere.[809] Two series of such antennas have been developed for nonradar countermeasures use. The first of these series consists of four antennas,[79, 80, 88] which are cylindrical with the maximum diameter of approximately 1 in. and length comparable with a quarter-wavelength at the center frequencies of their respective bands. This series covers the frequency range 200 to 850 mc. These antennas are retractable and interchangeable in a single mounting fixture and are primarily designed for use on relatively low-speed aircraft. The second series of antennas consists of two antennas made of streamlined tubing suitable for use on aircraft at speeds up to about 600 mph. The antennas cover the bands 100 to 200 mc and 190 to 450 mc, respectively, but are not easily interchangeable.

Faired-in Antennas for High-Speed Aircraft

Several types of relatively l-f faired-in antennas for particular applications have been developed where the frequency band is relatively narrow and where the radiation coverage is only over particular ranges of angle.[110, 113] Antennas of this type are very desirable for high-speed aircraft, but, when a reasonably uniform radiation pattern is necessary, the problems involved are extremely difficult to solve, especially for lower radio frequencies. The slot antennas used widely in radar countermeasures applications have not as yet been extended down in frequency range to include frequencies below about 100 mc. It has been suggested that a satisfactory solution to the problem of l-f coverage might be obtained by use of superaudible frequency switching between several antennas; however, this has not been tried.

Directly Fed Wing Antennas

Some consideration has been given to the use of a directly fed airplane wing (i. e., a plane whose wing tips are isolated from the rest of the wing and fed directly from lines running out through the inboard wing section) as an antenna for the lower radio frequencies. Preliminary results have not been too encouraging, since aerodynamical considerations prohibit insulating the wing tips for large distances. This means that wide-band coverage is very difficult to achieve.

4.4.3 Investigation of Hs-293 Antenna Directivity

A one-third scale model of the German Hs-293 glider bomb was constructed from information obtained from captured parts. A calibrated receiver was mounted inside the missile in such a way that the output meter was visible from the exterior and the whole was mounted in normal flight attitude on top of a wooden tower. Antenna patterns were obtained[47] in a horizontal plane for horizontally polarized waves, in a longitudinal vertical plane for horizontally polarized waves, and in a transverse vertical plane for horizontally polarized waves.

SECRET

Chapter 5

TEST METHODS, TEST EQUIPMENT, AND RADIO COUNTERMEASURES TRAINING

5.1 INTRODUCTION

A LARGE VARIETY of test methods and equipment has been developed in connection with the radio countermeasures [RCM] program. These can be divided roughly into two categories: first, equipment and methods which were developed for use in the laboratory for the furtherance of research and development work, and, second, methods and equipment which were designed for the adjustment and maintenance of RCM facilities in the field. Because of similar techniques involved, the related topic of RCM training is discussed in this chapter.

The majority of the work on test methods and equipment was done by the Radio Research Laboratory [RRL] under contract OEMsr-411; other important parts of the work were done by the General Electric Company under contract OEMsr-931, the Airborne Instruments Laboratory under contract OEMsr-1305, the Columbia Broadcasting System under contract OEMsr-867, and the General Radio Company under several contract numbers, especially OEMsr-1005 and OEMsr-923.

5.2 LABORATORY METHODS AND TEST EQUIPMENT

A considerable number of new techniques and devices were developed for laboratory use in connection with the research and development program of Division 15. This is not surprising, in view of the fact that the RCM investigations made covered practically the entire usable frequency spectrum, involved measurements of virtually all types (power, frequency, bandwidth, etc.), and frequently made use of extremely wide-band techniques.

Most of the important laboratory methods developed by the Radio Research Laboratory are discussed in a monograph;[809] the RRL developed methods which are not covered therein, together with laboratory test methods and equipment developed by the remainder of Division 15, are discussed in the following section.

5.2.1 Test Equipment for Communications Receiver Vulnerability Studies

The General Radio Company (under contract OEMsr-1005) undertook a development program to provide Jansky and Bailey (under contract OEMsr-1024) with various laboratory equipment needed for their work contract covering tests of the vulnerability of a-m and f-m communications receivers to various types of jamming (see Chapter 9). In order to simulate the various possible interfering signals it was necessary to provide signal generators capable of pulse modulation and of simultaneous frequency and amplitude modulation. The essential carrier-frequency range was from 20 to 156 mc, although some equipment was required to test lower-frequency a-m receivers. A suitable noise generator for noise modulation was also required.

The aim of the work was to provide relatively small numbers of the instruments developed. Also, it was important that the development program tie in as closely as possible with Jansky and Bailey's test program to provide generators for any particular frequency range when needed. Hence, the development schedule of this contract was planned in close cooperation with Jansky and Bailey. The experience of the Radio Research Laboratory at Harvard University and of the General Electric Company on radar jamming and frequency modulation, respectively, were made available to the General Radio engineers for this contract.

To test a communications receiver for vulnerability to jamming, two signal generators are necessary. One, which may be of a more or less conventional type, provides the desired signal. The second provides the jamming signal, which

SECRET

may be simultaneously amplitude- and frequency-modulated or pulsed. Since many of the receivers tested were f-m receivers and operated in a region where no standard f-m signal generators were available, two special generators were required for some of the tests.

Signal Generator, Type P-519

The first instrument developed was the Type P-519 signal generator, capable of amplitude modulation, frequency modulation, and pulsing, and covering the carrier range from 20 to 40 mc. Four of these units were constructed and delivered to Jansky and Bailey. These generators are of the beat-frequency type, in which the output frequency is varied by changing the tuning of one of the beating oscillators. Frequency modulation is obtained by a Miller-type reactance tube attached to the fixed oscillator circuit. Amplitude modulation and pulsing are applied to the mixer. A capacitance-type output attenuator was used.

Frequency Modulator, Type P-550

The second project, carried out simultaneously, involved the development of a reactance-tube modulator to be used with the General Radio Type 605-B standard signal generator over the carrier range between 1 and 20 mc. This provided satisfactory f-m signals for determining the effects of f-m interference on a-m receivers operating in this range. The instrument was known as the Type P-550 frequency modulator. A General Radio Type 605-B signal generator was also supplied to Jansky and Bailey for use with the modulator. This generator was specially modified to be capable of pulsing, and a Type 869-A pulse generator was supplied for this purpose.

Noise Generator, Type P-551

The third project involved the development of an audio-frequency noise source covering the range from 20 c to 20 kc, with a substantially constant noise output. The various noise generators developed in other laboratories were studied, and, on the basis of experience with these units, it was decided to use resistance noise to obtain the most even distribution of noise components in the spectrum. The amount of amplification required, however, made a straight l-f circuit unsuitable because of hum and microphonic difficulties, and a heterodyne system was used. In the resulting instrument, the P-551 noise generator, the noise is generated in a band at approximately 500 kc and heterodyned down to the audio-frequency range. The result is an extremely smooth amplitude-frequency characteristic. The instrument also includes both peak and rms voltmeters, and clipping circuits for adjusting the ratio of rms to peak voltage. The output power of the noise generator is sufficient for modulating the Type P-519 and other signal generators. The unit can also be used as a straight modulating amplifier for the Type P-519 generator when the latter is used with modulation sources of low power output.

Signal Generator, Type P-552

In the meantime, a fourth instrument, the Type P-552 signal generator, had been planned. This instrument was a more ambitious undertaking, since it was desired in this one unit to cover the entire carrier range from 20 to 156 mc in a single beat-frequency type signal generator.

One complete model of the Type P-552 signal generator was assembled, and parts have been made for three more. The project has been turned over to the Signal Corps for further developmental work. The generator consists essentially of two butterfly-type h-f oscillators operating at approximately 600 mc. Each is of the push-pull type utilizing two GL-446 lighthouse tubes, an arrangement which has been found to produce an unusually high degree of constancy of output voltage as the tuning is varied. One oscillator is variable over a range of 156 mc to provide the main tuning control. The other oscillator is variable over a narrow frequency range to allow for setting of the calibration and to provide an incremental frequency control for running selectivity curves. So far as possible, both oscillators are made exactly alike to provide a high degree of stability in the output frequency, which is the difference frequency between the two oscillators. A GL-446 lighthouse-type tube is used as

the mixer-detector and operates into a broad-band tuned amplifier. This in turn feeds through a constant-impedance, variable-capacitance type of volume control into a resistance-type attenuator. This combination provides constant output impedance at all frequencies and smooth adjustment of the output voltage from the minimum value up to the full capability of the instrument. Frequency modulation is applied to the fixed oscillator, and amplitude modulation and pulsing to the detector-mixer.

Signal Generator, Type P-553

Still another design was the Type P-553 signal generator, which covered the carrier range from 100 to 156 mc. This was of the master oscillator, tuned amplifier type with a Miller-type reactance-tube modulator operating directly on the oscillator. Amplitude modulation and pulsing were applied to the amplifying stage.

The signal generator development program was interrupted for the construction of the Type P-554 frequency multiplier, to cover the frequency range from 40 to 160 mc. In order to obtain a satisfactory test signal with a minimum of development time, this unit was built as a frequency multiplier rather than as a complete signal generator, and it was intended to be used in conjunction with a Type P-519 signal generator. The frequency multiplier doubles or quadruples the frequency of an f-m signal from the Type P-519. Provision for amplitude modulation is included in the frequency multiplier.

With the completion of the Type P-554 frequency multiplier, the entire frequency range planned for this contract had been covered with equipment suitable for the antijamming [AJ] tests. However, the tentative specifications for the Type P-552 signal generator, covering in one unit the frequency range from 20 to 156 mc, made this instrument seem unusually attractive as a general-purpose signal generator for use by the Armed Services and other government laboratories for many types of receiver testing. It was decided to continue this project to completion, since no such signal generator was available.

In all the equipment developed on this project, simplicity of control has been considered of paramount importance, so that a large number of tests can be run quickly and easily. Hence, all controls are direct reading. Output voltages and modulation percentages are indicated continuously and directly on panel meters, and trimmer or balancing adjustments have been kept to a minimum.

Miscellaneous Developments

In addition to the various special instruments developed for this contract, modifications of several standard instruments were also supplied to Jansky and Bailey. These included one General Radio Type 804-B signal generator, two Type 805-A signal generators, one of which was modified for pulsing, two additional Type 869-A pulse generators and various attenuators, resistors, etc., to allow Jansky and Bailey to construct the various coupling circuits required for connecting the generators to the receivers under test.

5.2.2 Spectrum Analyzers

Spectrum analyzers, preferably panoramic, are essential for many phases of RCM research and development, especially for the study of the behavior of oscillators under wide-band modulation. Two basic types of spectrum analyzers were developed by Division 15 contractors. One of these types provided a means (through a double-oscillator system) for obtaining frequency modulation of the local oscillator in the spectrum analyzer, which was essentially a superheterodyne receiver. Another type of spectrum analyzer consisted of a superheterodyne receiver with an extremely wide-band i-f amplifier. This wide-band i-f amplifier was used to feed a signal into a narrow-band sweeping receiver covering its entire bandwidth.

Spectrum Analyzer, 100 to 1,400 mc, Type OCC

Since no wide-range spectrum analyzers were available at the beginning of the magnetron program (see Chapter 3), a spectrum analyzer project was set up at the General Electric Company (under contract OEMsr-931) and a

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variety of techniques have been evolved for presentation of wide spectra in the range 100 to 1,400 mc, within which most of the low-power magnetrons are operated.

One spectrum analyzer design[134, 136] which has proved useful included as its basic component a superheterodyne receiver whose local oscillator is tunable over a wide range and can, at the same time, be swept over a narrower range at a 60-c rate. Attempts to sweep the narrow range mechanically were abandoned at an early stage, and the final design employs the beat between two 723-A/B X-band reflex klystrons as a local oscillator signal. One of these tubes is tuned over some 1,400 mc around its operating frequency. This requirement is not unduly severe since the operating frequency is of the order of 9,000 mc. The narrow sweep is obtained by varying the voltage on the reflector of the other 723-A/B. In this way a 60-c frequency modulation of the order of 50 mc is achieved.

The complete analyzer is shown in block diagram in Figure 1. The incoming signal to be analyzed is mixed with the signals from two 723-A/B's in a crystal which serves as a triple mixer. It then enters a 50-mc i-f channel about 1 mc wide. After two stages of amplification, it is converted to 4 mc and passes through one narrow-band (50 kc wide) stage. This stage defines the overall resolution of the device. For 60-c sweeping over a 50-mc range, 50 kc is the minimum bandwidth consistent with adequate

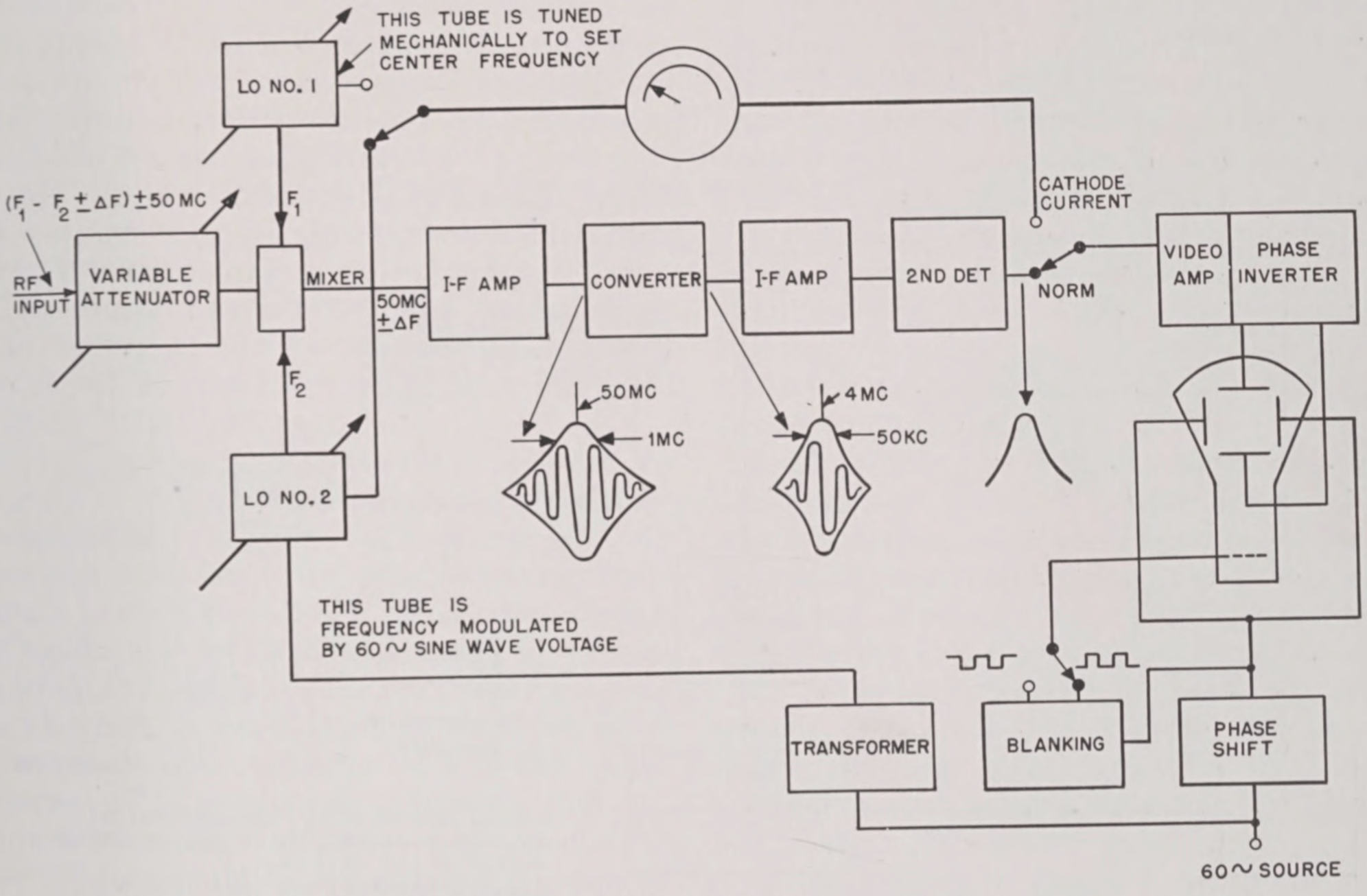


FIGURE 1. Block diagram of 100- to 1,400-mc spectrum analyzer.

amplitude response of the system. Finally, the signal is detected and amplified in a video amplifier in which particular attention has been paid to avoiding effects due to overloading from strong signals and to the l-f response which is extended below 50 c. Neglect of these factors results in a distorted picture on the panoramic presentation. The video signal is applied to the vertical plates of a 5-in. oscilloscope whose sweep is synchronized with the voltage which provides the frequency sweep on the local oscillator.

This equipment has been built in small lots in two versions. The first, or *RP-347 analyzer*,

is in a cabinet rack roughly 20x22x15 in. and weighs 135 lb. The second and final model is known as the *OCC analyzer*. It is about 16x16x18 in. and weighs about 125 lb. It meets Navy specifications and has been in limited production.

The sensitivity of this analyzer is such that a 100-μv signal will appear on the screen at about twice the noise level.

This analyzer can be calibrated in megacycles per inch of sweep on the face of the oscilloscope. Its absolute frequency calibration is approximate, since the absolute frequency of operation of the 723-A/B's is dependent to some extent on operating parameters. The input attenuator has been calibrated at one frequency but is slightly frequency dependent. No attempt has been made at image suppression in this instrument. As a result, a given signal appears twice as the instrument is tuned, at two points 100 mc apart (since the first intermediate frequency is 50 mc). Several other spurious images and harmonics appear at reduced intensity.

The spurious signals would be exceedingly troublesome if this instrument were to be used as a search receiver. As a laboratory instrument for spectrum analysis, used in conjunction with a calibrated signal generator, it has been quite useful.

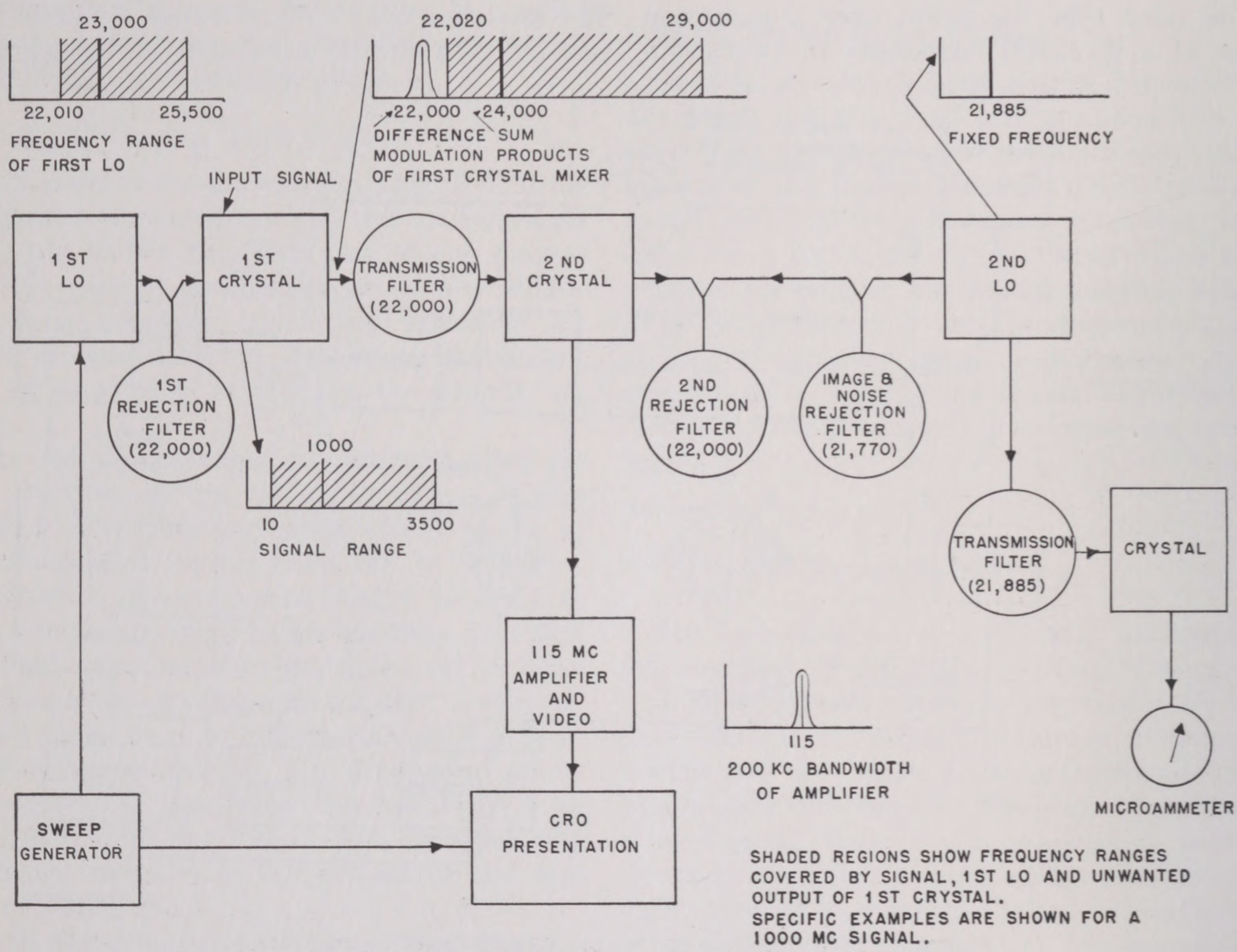


FIGURE 2. Block diagram of 10- to 3,500-mc spectrum analyzer.

SPECTRUM ANALYZER, 10 TO 3,500 MC

The Type OCC spectrum analyzer described above has three important drawbacks.

1. The main image and a number of spurious responses are present.
2. There is no accurate calibration of frequency.

3. The sweep frequency is not variable but is fixed at 60 c.

Another analyzer was designed and built, in which these undesirable features are minimized or eliminated. At the same time, the frequency range covered was extended considerably.

This analyzer[138] is also the double-superheterodyne type, but the intermediate frequencies are 22,000 and 115 mc instead of 50 and 4 mc. The circuits involved are shown in block diagram in Figure 2. The first local oscillator tunes from 22,010 to 25,500 mc so that the first crystal is really a modulator rather than a mixer.[140] The second local oscillator (a 2K33 "Oxford tube") runs at a fixed frequency of 21,885 mc and is held at this frequency by an AFC system. The first i-f channel at 22,000 mc consists of a tuned cavity. Suitable filters reject images and spurious responses.

The overall bandwidth of the system is defined by the 115-mc i-f channel which passes a band 200 kc wide. This amplifier is discussed in more detail later.

It will be clear from inspection of the block diagram in Figure 2 that images and spurious responses will undergo high attenuation. In practice it has been found possible to keep these signals down by at least 30 db. On signals strong enough to produce spurious responses, the amplifier design is such that limiting action occurs which gives warning of their presence.

The first local oscillator is a Z-668 reflex klystron. It is mechanically tunable over the required range and can be frequency-modulated over 60 to 80 mc by sweeping the reflector voltage. All but 30 mc of this range is compressed near the ends of the active range, but expansion of the various regions of the range is possible.

The frequency of the sweep is normally 60 c but can be varied if desired.

The sensitivity of this analyzer is such that a 100-μv signal applied across 50 ohms appears at twice the noise level.

Over the frequency range 500 to 3,500 mc, an accurate frequency marker permits absolute frequency determination within 5 mc. This marker is generated in a spark-excited, tunable, calibrated resonant line which is similar in construction to a standard coaxial wavemeter.

Production of this analyzer was held up indefinitely by the lack of a procurement program on the Z-668 first local oscillator, which, apparently, has no other applications than this one. This situation has necessitated the evolution of compromise designs using standard tubes and discussed in the next section.

Other Spectrum Analyzer Considerations (Sweeping Local Oscillator Type)

Many modifications of the above designs and incidental studies to improve them have been made. A wide-range spectrum analyzer[142, 157] similar to the analyzer described above has been developed. Several important changes have been made to permit the use of commercially available thermally tuned K-band tubes and to improve the overall performance of the analyzer. These changes are as follows.

1. The first local oscillator is a Western Electric Type 1462 tube (which is a developmental Type 2K50) tunable over the range 24,600 to 21,600 mc.

2. The first transmission filter is set at 24,600 mc to match the 1462 range and is double-tuned to give a wider band and minimize the stability difficulties experienced with thermally tuned tubes. The double-tuned circuit shows materially improved off-band rejection.

3. The improved selectivity of the first transmission filter made it possible to eliminate the image- and noise-rejection filter.

4. The second local oscillator is a 2K50 tube and is held on frequency by an AFC circuit.

5. The frequency marker is a K-band wavemeter inserted in the wave guide adjacent to the first local oscillator. With this marker it is possible to calibrate the analyzer over the whole 10- to 3,000-mc range.

This analyzer has been in limited production.

Narrow-Band Amplifier, 115-mc. One of the spectrum analyzers described above uses a second i-f channel 200 kc wide at 115 mc. This channel was required to be logarithmic in response over a range of 35 db and to saturate at the upper limit of this range.

The narrow bandwidth has been achieved by using capacity-loaded coaxial lines as resonant circuits. Used in the grid circuits of the amplifier, these resonant circuits achieve a

Q of 300, so that with seven stages of amplification the narrow bandwidth is easily obtained. A very close approach to a logarithmic response is achieved by operating in the correct region of the characteristic of 6AK5 pentodes.

A photograph of the amplifier strip which also includes a second detector and video amplifier is given in Figure 3.

A variable input impedance has been incorporated in this amplifier by the introduction into the input circuit of a three-plate condenser, with two fixed plates in the grid circuit of the input tube and a movable intermediate plate to which the input is connected.

Studies on Crystals. The spectrum analyzers described above employ the heterodyne principle in an abnormal fashion, in that the intermediate frequency is close to that of the local oscillator and the input signal frequency is low compared with both. The crystal mixer is thus used as a modulator, rather than as a converter.[140] The crystal mixer plus local oscillator system has frequently been treated theoretically as a four-terminal network with an h-f output, that is, with the normal heterodyne connections. The reciprocity theorem allows the results to be used for a system in which input and output are interchanged. In mixer systems

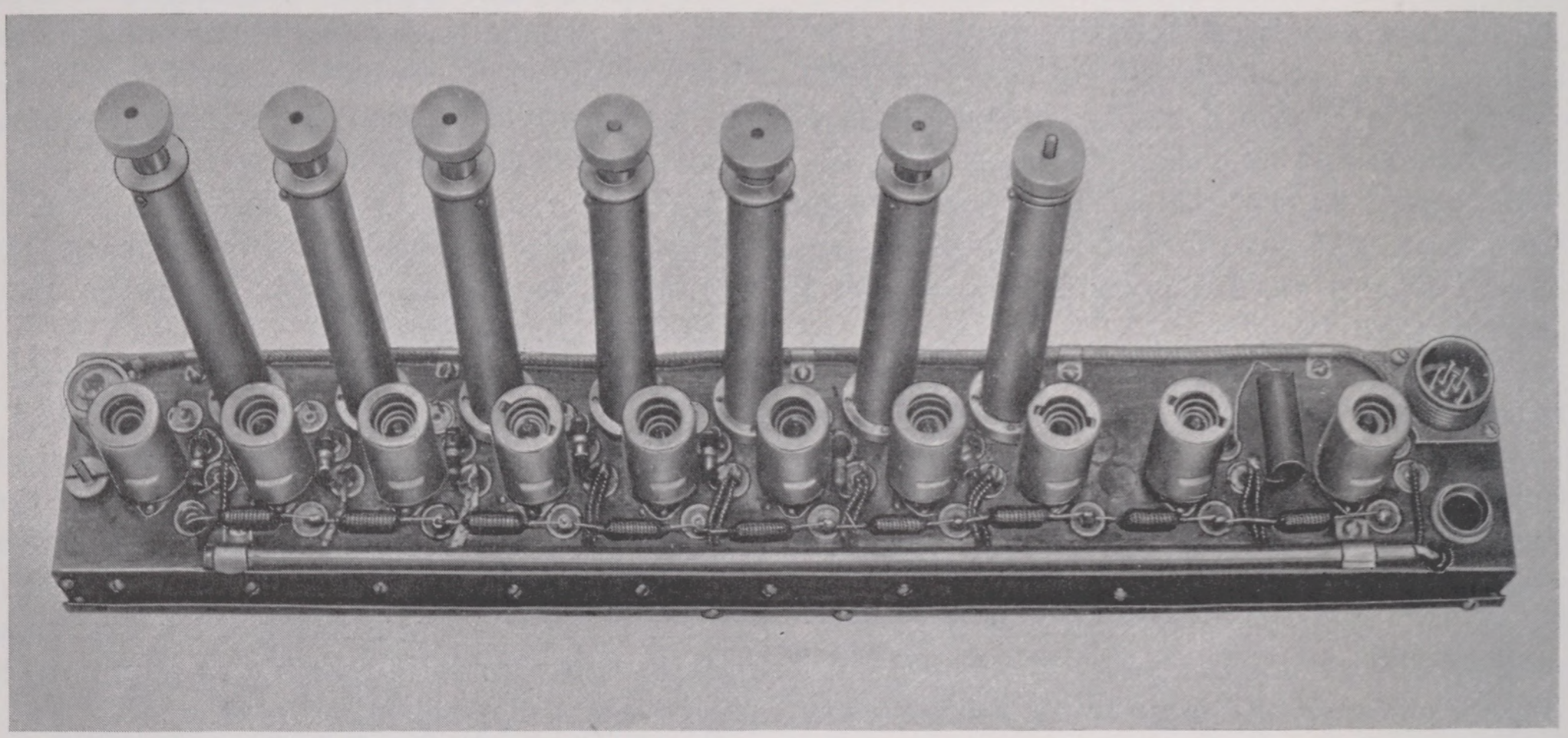


FIGURE 3. 115-mc center frequency narrow-band amplifier.

It has been demonstrated that the bandwidth of this amplifier can be made as small as 50 kc by introduction of regeneration.

Impedance Bridge 115-mc. To permit impedance measurements in connection with the 115-mc narrow-band amplifier described above, a Schering impedance bridge[847, 848] was constructed. Particular attention was paid to the physical size and component arrangement for this bridge, so that it was possible to avoid the use of two compensating components.

This impedance bridge is used to measure impedances from 50 to 500 ohms. The accuracy of these measurements is adequate to make the bridge a useful tool in the design of amplifiers for this frequency range.

employing silicon crystals, deductions from the reciprocity theorem are borne out by experiment. If germanium crystals are used, however, the theorem appears to break down. Germanium crystals have several desirable properties when used as modulators—in particular, very low conversion losses are attainable. To clarify this situation, a program was initiated to investigate the four-terminal network in which the germanium crystal is used as a modulator.

The reciprocity theorem has been shown to be totally unreliable in the case of germanium crystals.[139, 143] In some cases the theorem fails to predict the improved behavior of germanium as a modulator, and in others germanium crystals are less satisfactory as modulators than the

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theorem would predict. The theoretical implications of this work were not fully understood.

Wide-Band Intermediate-Frequency Spectrum Analyzers, TS-54/AP

A portable instrument covering the frequency range 80 to 1,000 mc, which is suitable for either laboratory or field use, has been developed by Radio Research Laboratory (under contract OEMsr-411). This spectrum analyzer[351, 352, 810] has been produced in reasonable quantities and was rather widely used, both for laboratory and field applications. It is especially useful in the field for determining the barrage spectrum furnished by a number of jamming transmitters set for adjacent channels.

The techniques of the oscillator design, mixer design, etc., which were used in this spectrum analyzer have been discussed elsewhere.[809] A block diagram of the unit is shown in Figure 4. The principle of operation is as follows.

By means of a tunable oscillator, hereinafter referred to as the first oscillator, and an untuned crystal mixer, all input signal components within any 20-mc band situated in the range 70 to 1,000 mc are converted by the heterodyne process to related components lying in the 20-mc band between 20 and 40 mc. Input signals below 500 mc heterodyne with the fundamental frequency of the first oscillator to produce the aforesaid conversion, and those above 500 mc heterodyne with the second harmonic of the oscillator.

The difference-frequency components at the output of the crystal mixer are fed to an i-f amplifier which has a substantially constant gain between 20 and 40 mc. The output of this amplifier is fed to a second (vacuum tube) mixer, where another heterodyning process is accomplished with the aid of a second oscillator tunable from 20 to 40 mc. The related difference-frequency components resulting from this second conversion are amplified by a video amplifier which amplifies uniformly all frequency components contained in a 100-kc portion of the i-f pass band (this is the "resolving power" of the instrument). Since the amplitudes of the components in the i-f amplifier are also proportional to those of the input signal components and the output of the video amplifier is proportional to the components present in the i-f amplifier, the output of the video

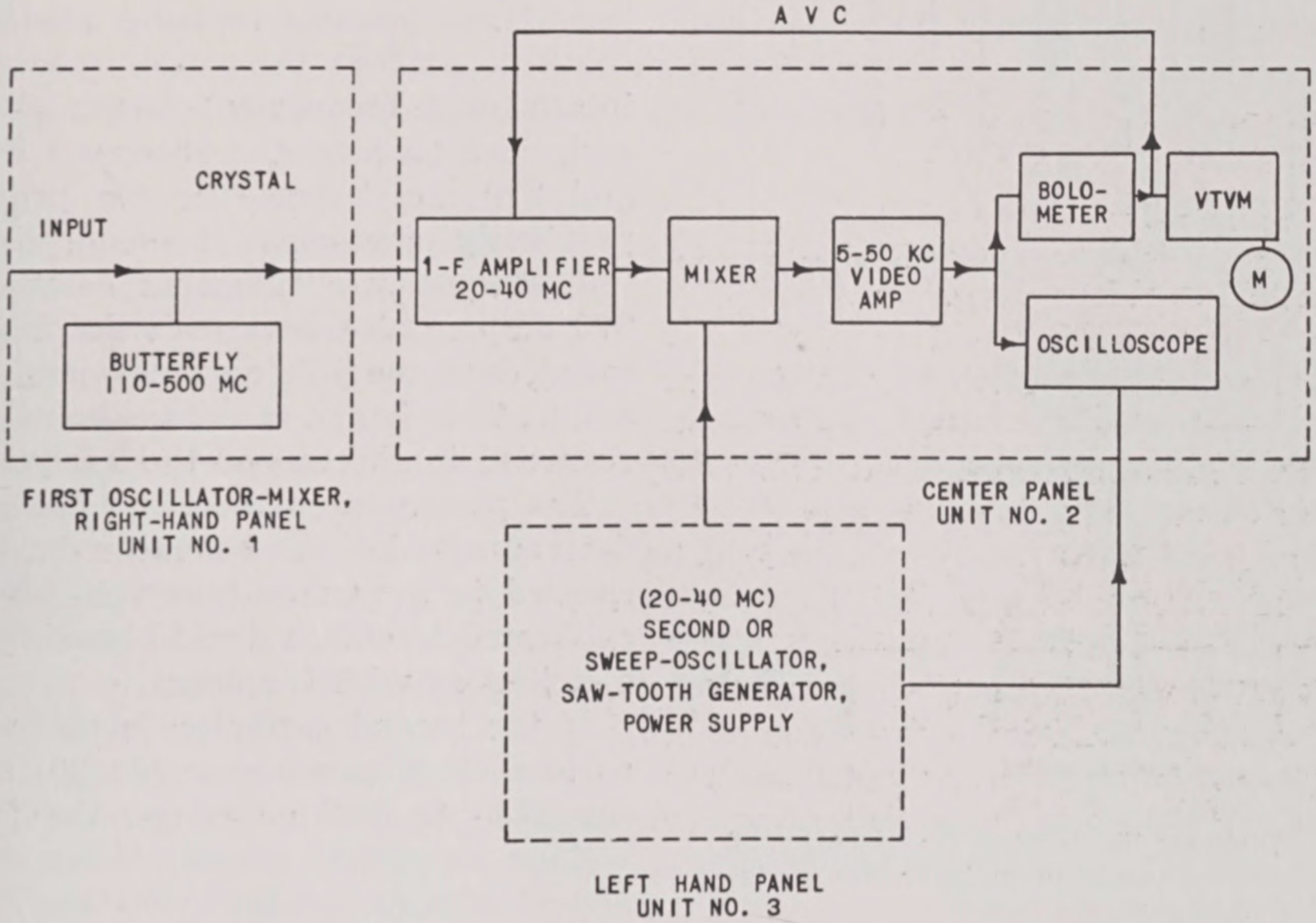


FIGURE 4. Block diagram of 70- to 1,000-mc spectrum analyzer.

amplifier is a function of the signal input contained in any desired 100-kc portion of the input signal. The location of this 100-kc portion with respect to the input signal band is dependent upon the setting of the first and second oscillators. The first oscillator is manually tuned and the second oscillator can be tuned manually or automatically driven by a motor, which makes possible the visible presen-

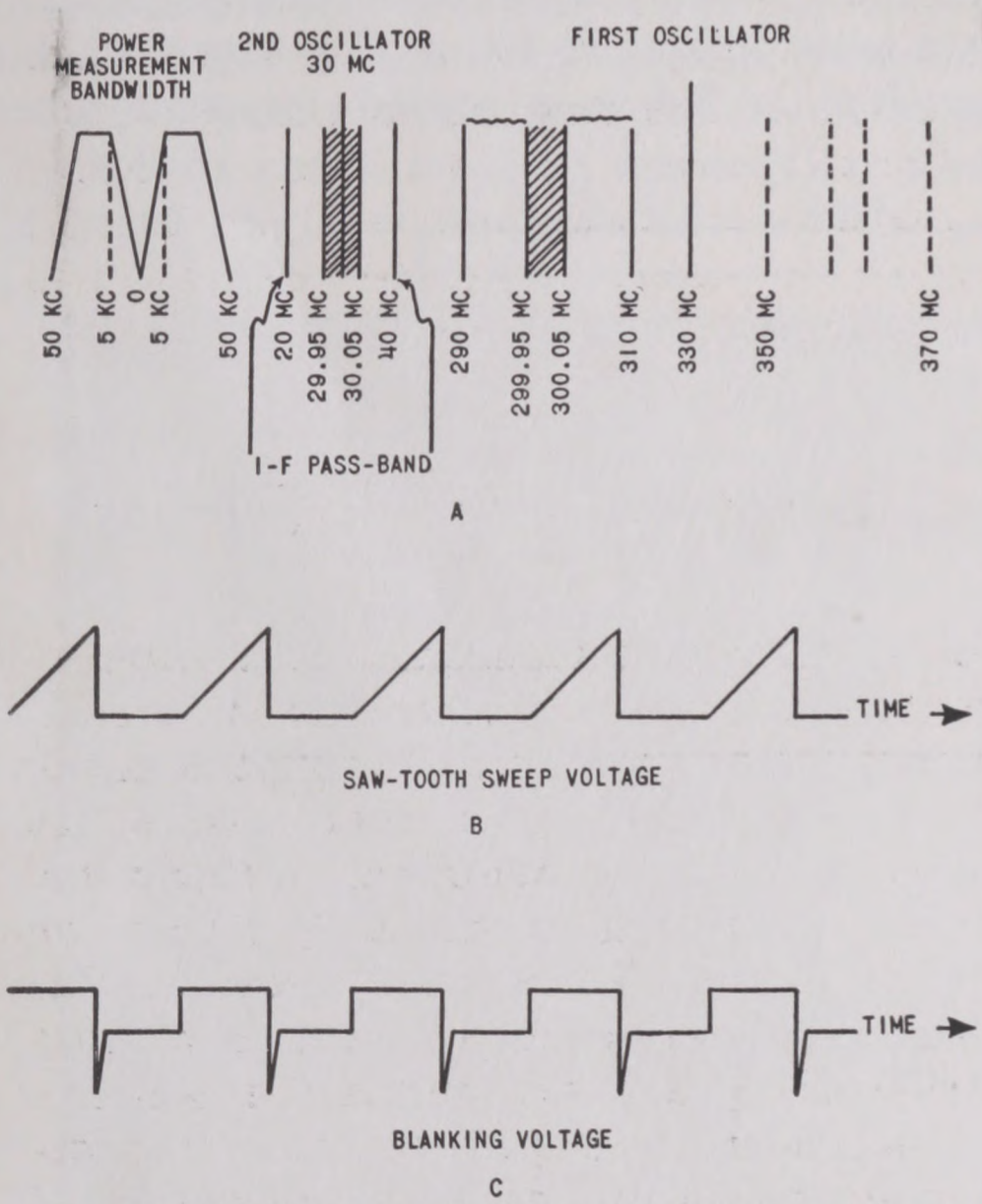


FIGURE 5. Diagram illustrating the operation of the 70- to 1,000-mc spectrum analyzer. For an explanation of the figure, see text.

tation of the spectrum of a signal on the oscilloscope screen. The output of the video amplifier can be applied to a bolometer measuring circuit or to the vertical deflecting plates of the cathode-ray tube.

The double-conversion (two mixers) system, described in the function of the spectrum analyzer, yields both a wide-tuning range and an analyzing bandwidth (100-kc resolving power) which are constant and independent of the frequency of the signal.

A graphical representation of the functioning of the spectrum analyzer can be reviewed by reference to Figure 5. In this example, the spectrum to be analyzed is located between 290 and 310 mc. The first oscillator, tuned to 330 mc, heterodynes with the components in the band 290 to 310 mc to produce difference-frequency components between 20 and 40 mc. The second oscillator, tuned to 30 mc, then heterodynes with the latter components and likewise produces difference-frequency components; those whose frequencies are less than 50 kc are amplified by the video amplifier. Thus, the output of the video amplifier is proportional to the components of the original input lying between 299.95 and 300.05 mc. When the frequency of the second oscillator is varied by hand, it is possible to move the 100-kc band so as to explore the entire spectrum in the intermediate frequency between 20 and 40 mc, and, consequently, the spectrum between 290 and 310 mc, because of the proportionality previously mentioned. It should also be noted that frequency components between 350 and 370 mc can also beat with the first oscillator to produce the i-f frequency used in the example. This image response should not be disregarded in the use of the analyzer.

The power output of the video amplifier is determined by a bolometer-bridge circuit coupled to a vacuum-tube voltmeter which is calibrated to obtain decibel readings of power distribution with frequency.

If the second oscillator is motor-driven, so as to cyclicly sweep over the 20- to 40-mc or the 27.5- to 32.5-mc range, the proportional voltage amplitude corresponding to all component signals between 290 and 310 mc or 297.5 and 302.5 mc can be delineated as a function of frequency on an oscilloscope. This feature has been made a part of the spectrum analyzer by the inclusion of a calibrated, 2-in. cathode-ray tube. Provisions for connecting an external cathode-ray oscilloscope are included.

5.2.3 Miscellaneous Laboratory Test Methods and Equipment

A number of relatively unrelated miscellaneous developments were undertaken by several Division 15 contractors. Several of the devices produced are described below, and a consider-

ably larger number of them are described in the accompanying monograph.[809]

High-Frequency Calorimetric Wattmeter

Chapter 3 described the development of magnetrons operating in the 100- to 1,600-mc range. At the time this development program was initiated, no simple techniques were available for speedy measurement of power over wide frequency ranges at these frequencies. It was necessary, therefore, to develop such techniques.

The first wattmeters tested were sections of lossy coaxial line, usually at least 30 ft long, which were cooled by water flowing in the annular space between the outside of the line and a coaxial external copper tube. Measurements of entrance and exit water temperatures and rates of water flow gave reliable measurements of power dissipated, but the system required several minutes to come to equilibrium and end reflections caused difficulties at low frequencies, even for 50 ft or more of line.

The power-measuring load consists of a short glass tube, usually an inch or two long, connected across the oscillator tank circuit at the point at which an external load would normally be attached. Through this load flows salt water whose salinity is adjusted until the resistance from end to end of the glass tube is equal to the normal resistive load—usually 50 ohms. The ends of the tube are sealed to short Fernico sections which are clamped to the appropriate points on the oscillator tank circuit. The salt water is pumped through a heat exchanger where it is cooled by tap water. The power dissipated in the salt water follows, as before, from measurements of entrance and exit temperatures of the salt water and of the rate of salt-water flow. This system comes to equilibrium in a few seconds. It has proved equally satisfactory at all frequencies up to at least 2,000 mc and has been operated at power levels up to over 2 kw.

Coaxial versions of this load have been designed for terminations for coaxial lines.

Miscellaneous Items

A very considerable number of miscellaneous items of more or less conventional design were required in the research and development program. These included instruments of virtually every type. Many of these are described in the chapters of this volume or of the accompanying monograph[809] dealing with the developments in connection with which the items were used. Specifically, these developments included synthetic radar sets, copies of enemy radar sets, various types of noise-analyzing equipment, wattmeters, crystal voltmeters, wide-band oscilloscopes, frequency meters, special tube-test sets, antenna-measuring equipment, and a number of other devices. For references to complete descriptions of these test equipments and methods, see the sections on test equipment in the Appendix.

5.3 TEST EQUIPMENT FOR FIELD USE

As for all radio equipment, it is essential to supply adequate test equipment for the adjustment and maintenance of RCM facilities. Aside from the test equipment commonly used for the maintenance of radio apparatus, probably the most important item in the RCM field is an accurate and stable frequency meter. As has already been pointed out in the introductions to the receiver and the transmitter sections, this instrument is essential for accurately determining the exact operating frequencies of enemy communications and radar channels and for setting jammers to these frequencies.

Next in importance for maintenance of transmitters are instruments for checking the power output of the transmitters and their modulation capabilities. In the maintenance of receivers, test oscillators or signal generators are useful for checking the performance in the various frequency bands.

Test equipment needed for the maintenance of communications countermeasures facilities is, with minor exceptions, quite standard and required but little of the development time of Division 15 laboratories. In the case of radar countermeasures test equipment, on the other hand, the wide frequency coverage required in frequency bands hitherto unused demanded the development of virtually a complete line of

frequency meters, power-measuring devices, etc., over the range 100 to 10,000 mc.

5.3.1 Radar Countermeasures Test Equipment Needs

Accurate means for measuring frequencies are essential in RCM receiving and transmitting activities. In receiving activities, it is important to keep a careful check on the frequencies that are used by the enemy; in transmitting, means are required for accurately adjusting the transmitters to those frequencies. The presetting of transmitter frequencies with sufficient accuracy for spot jamming is not generally feasible. For barrage jamming, however, not only is it feasible to do this, but from a practical standpoint it is essential to do so. This point is discussed in somewhat greater detail in Chapter 11.

If the same frequency meter can be used both for measuring the enemy frequency and for adjusting the jammer, the absolute accuracy of the meter is not too consequential. Its stability, as a function of temperature, humidity, and pressure (altitude), may be very important, however.

A simple but effective method of accurately setting spot jammers is to make use of an insensitive, narrow-band receiver which is tuned to the victim frequency and subsequently used to monitor, not only the jamming transmitter, but also the victim signal. This method is even more convenient in case the receiver used employs panoramic presentation of a relatively wide frequency range. Receivers and receiver modifications for this type of use are described in Chapters 10 and 11.

The need for equipment to measure the power output of transmitters on the test bench is self-evident and equipment suitable for this purpose was developed. In addition, however, it is prudent to check the performance of such transmitters after they are installed and connected to their regular antennas. This may be done with simple crystal probes and similar devices. Although checks of this kind are qualitative, they are very useful, since, being made under actual operating conditions, they are comprehensive and will, therefore, expose shortcomings of the overall system.

The distribution of the energy in the side bands of a barrage jammer is often a function of the particular tuning adjustments that are used. Some transmitters are more critical than others in this respect. With such transmitters, the use of some simple means for determining the shape of the sideband energy-distribution curve is desirable. In addition to the spectrum-analyzing devices and the panoramic-receiving attachments mentioned above, which can obviously be used for this purpose, it is often possible to employ other relatively simple devices for specific applications. One device of this type is the so-called double-peaking amplifier-alignment unit, which assures proper alignment of a wide-band amplifier used as a part of many barrage jammers by adjusting the two peaks of the response curve of the amplifier so that they have the proper frequency separation.

Sometimes the complete absence of signals in a certain band of frequencies (generally the very high ones) made it impossible to ascertain whether a receiver operating in this region was in good working condition. As may well be appreciated, after many hours of fruitless search over a band of frequencies wherein no signals are present doubts may exist concerning the functioning of the receiver. Test oscillators, capable of supplying a signal at the frequencies in question, are very useful for checking the performance of receivers under these circumstances.

For more careful measurements on the test bench and for alignment of the various tuned circuits in the receiver, use can be made of standard signal generators. Standard signal generators differ from test oscillators in that known and adjustable output voltages are available, either unmodulated or modulated to a known degree by waves of various forms.

The importance of having adequate test equipment available for the maintenance and repair of RCM facilities cannot be overemphasized. The units mentioned above are only those which have been specifically developed for, or are particularly applicable to, the RCM field. In planning complete servicing facilities, therefore, it is essential to make provision not only

for the various standard types of radio test and servicing equipment but for items demanded by the considerations mentioned above.

5.3.2 Summary of Test Equipment Developments

The Division 15 RCM test equipment developments are summarized in Table 1. The bulk of these projects were undertaken by the Radio Research Laboratory (under contract OEMsr-411). Division 15 activity in this field was supplemented by commercially available test equipment in this frequency range, and by Service laboratory developments described elsewhere. The equipment represented here, however, comprises a very large percentage of the total required for the comprehensive RCM program and thus represents a fair solution to the requirements mentioned above.

It was not found necessary to develop special field-type test equipment for nonradar RCM needs.

5.4 RCM TRAINING

Closely related to the subject of test equipment and methods because of similar techniques is the problem of providing proper aids to RCM training. Both the use of countermeasures and the defense against enemy use of countermeasures depend very strongly upon the skill of the personnel involved, so a very considerable training program was undertaken by the Armed Services. Division 15 of NDRC participated in this program, both by furnishing instructors for early training courses and by developing specific equipments and aids to be used by the Armed Services in their training program.

5.4.1 Training Courses

In the early days of countermeasures development, the subject was so new and novel that it was necessary to train the Armed Services personnel who were going to be responsible for operational use of the equipment being developed at various research laboratories. RRL gave about fifteen 1- and 2-week training courses to groups averaging thirty officers. The trained personnel thus provided did the early operational application of countermeasures and also formed the nucleus for the later extensive program instituted by the Army and Navy for RCM training.

A closely related activity of RRL was the preparation of sound motion pictures for training use. These films[668] covered such subjects as operation of transmitters, use of direction-finding equipment, etc.

TABLE 1. Summary of field-type test equipment.

Identification Nos.	Use	Tuning range (mc)	References	Comments
		Signal sources		
RRL: A-1501 Div. 15: RP-173	Test oscillator.	1,000-3,000	507	
RRL: A-1700 Div. 15: RP-191	Jamming signal generator.	2,400-3,700	347	Includes provisions for virtually all types of modulation. Designed for laboratory and field use in studying susceptibilities to jamming of radar sets, and as a standard signal source in this frequency range.
RRL: A-2651 Div. 15: RP-292	Test oscillator.	2,500-3,500	349, 464	Pulsed fixed frequency signal source, variable over specified tuning range by fairly complex adjustments.
RRL: F-2200 Div. 15: RP-289 Army/Navy: TS-52/APQ-1	R-f pulse generator.	460-600	358	For use as simulated radar for checking operation of automatic lock-on jamming transmitters.

TABLE 1.—(*Continued*)

Identification Nos.	Use	Tuning range (mc)	References	Comments
RRL: Q-2105 Div. 15: RP-286	Test oscillator.	5,000-10,000	809	
RRL: U-800 Div. 15: RP-306	Microwave test oscillator.	1,500-3,500	811	
RRL: U-1100 Div. 15: RP-476 Army/Navy: TS-406/UP	Test oscillator.	1,000-3,500	812	Consists of resonant cavity using buzzer for excitation.
RRL: U-1150 Div. 15: RP-476	Test oscillator.	3,000-10,000		Same as U-1100 except for type of cavity.
RRL: U-1500 Div. 15: RP-469 Army/Navy: TS-403/U	Standard signal generator.	1,800-4,000	769	
GR: P-523A RRL: U-500 Div. 15: RP-195 Army/Navy: TS-47/APR	Test oscillator.	40-500, harmonics useful to 3,000.	448	
GR: P-525A Div. 15: RP-160 Army/Navy: AN/TPQ-T2	Signal generator.	90-270	123	Also useful for AJ training.
RRL: M-3010 Div. 15: RP-298	Test oscillator.	270-280		Test oscillator for use in checking directivity patterns of direction-finding equipment.
		Frequency meters		
RRL: B-2700 Div. 15: RP-294 Army: BC-1255A	Heterodyne frequency meter.	70-145	356	Superseded by RRL U/B-3000.
RRL: U/B-3000 Div. 15: RP-245 Army/Navy: TS-99/AP	Heterodyne frequency meter.	60-225	359	Harmonic operation up to 1,000 mc.
RRL: U/B-3100Y Div. 15: RP-293 Army/Navy: TS-92/AP	Double-peaking alignment device.	20-500	402	For adjusting double-peaked amplifiers of bandwidths 0.2-7.0 mc.
RRL: Y-700 Div. 15: RP-293	Double-peaking alignment attachment.	20-500	446	Plug-in attachment for use with communications receivers tuning from 0.5-7.0 mc, to perform same function as RRL U/B-3100Y.
RRL: F-3600 Div. 15: RP-290 Army/Navy: TS-53/AP	Transmitter test set.	200-450 400-700		Combination frequency measuring and power-output measuring device for checking operation of transmitters.
RRL: F-4000 Div. 15: RP-306	Wavemeter.	240-450, 400-700. Also 700-1,500 by harmonic operation.	813	Coaxial wavemeter.

TABLE 1.—(*Continued*)

Identification Nos.	Use	Tuning range (mc)	References	Comments
		Power measurements and miscellaneous		
RRL: F-2300 Div. 15: RP-290 Army: CV-9/APT Army/Navy: TS-157/AP	Transmitter output indicator.	Untuned	629	Crystal probe for checking transmitter output. Various mounting modifications were developed.
RRL: Z-1600 Div. 15: RP-306 Army/Navy: TS-118/AP	Thermocouple wattmeter.	Up to 1,000	386	
RRL: H-300 Div. 15: RP-306	Noise analyzer.		595	Measuring device for studying the spectra of various noise sources.
RRL: U-440 Div. 15: RP-266	Tube tester for Type 931 electron multipliers.		416	Used for testing Type 931 tubes as noise sources.

5.4.2 Training Equipment Development

A number of devices especially adapted to use in training operators to recognize and combat jamming were developed. Still other devices were developed for training operators in the use of RCM transmitters and in the use of RCM direction-finding equipment.

RADAR OPERATOR TRAINING AIDS

It was recognized quite early that some provisions should be made for training radar operators to recognize and combat any jamming that they might encounter. The first equipment developed for this use consisted of modifications of then existing jamming transmitters. The so-called Carpet (450 to 720 mc) and Rug (200 to 550 mc) transmitters (see Section 11.3.1) were modified[456] so as to provide sine wave and pulsed operation as well as noise-modulated operation. There was also developed a small plug-in unit[415, 456] for use with almost any radar jamming transmitter provided with noise modulation, which served to remove the noise modulation from the transmitter and substitute sine wave or pulse modulation. These units were especially useful in training operators in the use of antijamming devices (see Chapter 13).

A number of special signal generators were also developed which proved useful in operator training. Two of these (RRL A-1700 and GR P-525A) have already been mentioned in Table 1 as standard field test equipment. Another similar training signal generator[814] was developed for the frequency range 500 to 1,000 mc, especially for use in conjunction with the Navy Mark IV radar. A still further development along this line was the TS-109/SPA interference generator,[815] which was an attachment for the Mark I trainer for the Mark III and Mark IV radars.

SPOT-JAMMER OPERATOR TRAINING

The American-British Laboratory undertook a considerable program of training operators for the Eighth Air Force in spot-jamming technique. This activity necessitated the development of synthetic radar transmitters and mocking-up of special installations which resembled those used operationally.

DIRECTION-FINDING TRAINERS

A ground trainer to assist in training Ferret RCM observers the proper methods of direction finding (AN/APA-24 and other systems) was developed. A prototype model was constructed for the Army Air Forces.

Chapter 6

THEORETICAL STUDIES AND MISCELLANEOUS DEVELOPMENTS

6.1 INTRODUCTION

THE ORIGIN and development of equipment necessary for the successful prosecution of the radar countermeasures program in many cases required considerable recourse to theory, not only because of the extremely varied nature of the problems encountered, but also because it was often necessary to determine the feasibility of an idea or project before the design and construction of equipment was undertaken. Then, too, once the apparatus had been made, it was often necessary to estimate its operational capabilities in different tactical situations. Theoretical studies of both the "basic" and the operational type were carried out, covering a wide range of problems involving noise, frequency modulation, propagation, confusion reflectors, transformer design, and so forth (to name a number of the more important topics). A summary of the theoretical work carried out under the auspices of Division 15, along with an account of miscellaneous developments, appears in this chapter. This work was carried out by various laboratories including the Radio Research Laboratory (under contract OEMsr-411), the Airborne Instruments Laboratory (under contract OEMsr-1305), and the Bell Telephone Laboratories (under contract OEMsr-966).

6.2 STUDIES OF JAMMING SIGNALS

Because of its importance as a limiting factor in electronic performance, a detailed study of noise, with special emphasis on its jamming properties, was undertaken in an effort to aid experiment along these lines and to answer a large number of general questions regarding the obscuring of the detection of radar signals by noise and, to a lesser extent, the obscuring of communications by noise.

6.2.1 Basic Noise Studies

One of the first problems considered concerned the general (theoretical) shape of the output spectrum from a jamming transmitter broadcasting noise or a noise-modulated wave. To jam successfully one or more channels (spot or barrage) a complex interfering signal is required to obscure the radar pip on the receiver screen (see Chapter 13, Section 13.3.2). Noise was suggested early in the program as having the necessary characteristics. Further, a broad and reasonably uniform output spectrum, of sufficient spectral intensity, is a minimum requirement. Spectral breadth is needed to cover the desired channels, and uniformity to provide enough radiated energy in a particular frequency range to obliterate the enemy's signal. With these attributes in mind, it was also suggested that frequency modulation by a continuous wave of suitable form might provide, in conjunction with noise, the needed breadth and uniformity.

Noise Modulations

A study of five different types of transmitted waves involving noise and continuous wave was accordingly undertaken.[525] The general spectrum of the output when simultaneous but uncorrelated frequency and amplitude modulation of a carrier (of frequency f_c) by random noise takes place, along with frequency modulation by a sine wave of frequency f_0, was determined to be

$$W(f) = \frac{\hat{E}_0^2}{2} \sum_{-\infty}^{\infty} J_n^2(b) \lim_{T\to\infty} \int_0^T \left(1 - \frac{u}{T}\right)(1 + A(u))e^{-B(u)} [\cos(n\omega_0 + \omega)u + \cos(n\omega_0 - \omega)u]\, du, \quad (1)$$

where frequency f is measured from carrier f_c, $\hat{E}_0$ is the peak amplitude of (un-modulated) carrier, and $A(u)$ and $B(u)$ are even functions:

$$A(u) = \frac{\gamma^2}{\hat{E}_0^2}\int_0^\infty W_A(f) \cos 2\pi u f df,$$

$$B(u) = \frac{\lambda^2}{2\pi^2}\int_0^\infty W_B(f) \sin^2 \pi u f df. \quad (2)$$

Here $W_A(f)$ and $W_B(f)$ are the spectra of the amplitude and frequency (or phase) modulating noises respectively, γ and λ are constants determined from the specific conditions of modulation, and $J_n(b)$ is an nth-order Bessel function of the first kind. The quantity b is equal to $A_0/2\pi$, where A_0 is the peak voltage of the sinusoid producing the continuous-wave [c-w] frequency modulation; b is also known as the modulation index, defined as

$$b \equiv \frac{\text{Frequency deviation } \Delta f \text{ about a central frequency } f_c}{\text{Frequency } f_0 \text{ at which the above deviation is made}}.$$

It is found convenient to define a modulation index for noise, $1/k$, where, in analogy to the quantities in b, we may write

$$\frac{1}{k} = \frac{f_s}{f_a} \equiv \left| \begin{array}{l} \text{Frequency departure from the carrier } f_c \text{ for a steady (d-c) modulating voltage equal to the rms noise voltage divided by the upper frequency limit to the noise band used for modulation.} \end{array} \right. \quad (3)$$

The frequency f_a may be chosen at some suitable place, say the half-power point.

Results for the five cases considered may be summarized as follows.

Case I: Frequency or Phase Modulation by Random Noise Alone. This problem was examined originally by the Bell Telephone Laboratories, Inc.[834] The spectrum, obtained as a special case of equation (1), is

$$W(f) = \frac{\hat{E}_0^2}{2f_s} \sum_{m=0}^{\infty} (-1)^m d_m \phi^{(2m)}\left(\frac{f}{f_s}\right)$$

where $$\phi^{(j)}(x_0) \equiv \left. \frac{d^{(j)}}{dx^j} \frac{e^{-x^2/2}}{(2\pi)^{\frac{1}{2}}} \right|_{x = x_0} \quad (4)$$

and for frequency modulation by a uniform band extending from $0 < f < f_a$, these values are obtained:

$$d_0 = 1, d_1 = 0, d_2 = \frac{k^2}{3 \cdot 4!}, d_3 = \frac{-k^4}{5 \cdot 6!},$$
$$d_4 = \frac{-k^4\left(\frac{k^2}{7} + \frac{35}{9}\right)}{8!} \cdots. \quad (5)$$

For phase modulation by a uniform band extending from 0 to f_a it is equivalent to consider frequency modulation by noise whose spectrum is proportional to f^2, $0 < f < f_a$. Then the d_m's of equation (4) become

$$d = 1, d_1 = 0, d_2 = \frac{3k^2}{5!}, d_3 = \frac{3k^4}{7!},$$
$$d_4 = \frac{3k^4}{9!}\left(k^2 + \frac{1701}{5}\right) \cdots. \quad (6)$$

The result is approximately a gaussian (or normal) energy distribution in the practical cases $k < 1.0$, which generally is not sufficiently uniform or broad for barrage jamming.[a] However, this type of modulation has the favorable sideband to total energy ratio of 1:1.

Case II: Amplitude Modulation by Noise Alone. Here the output spectrum is simply

$$W(f) = \frac{\gamma^2 W_A(f)}{4} + C^2\delta(f - 0), \quad (7)$$

where C^2 is the mean-square amplitude of the carrier component, and $\delta(f-0)$ is a delta function with the property that it is infinite at $f = 0$ and zero elsewhere, according to the customary definition. It is possible in this method to produce a fairly uniform spectrum, but it is not easy to make the barrage wide. There is always the difficulty that considerable energy is retained in the carrier. Even with extreme clipping, which is mentioned later, half the energy remains in the carrier. (The question of the influence of clipping on the spectrum and other properties of noise is considered below.) It was shown that clipping does not seriously impair the uniformity of the spectrum, but it may give an undesirable "ceiling" in the oscilloscope pattern unless the receiver width is narrow compared to that of the barrage.

Case III: Frequency Modulation by a Sine Wave. If there is no noise modulation of any kind, but only the frequency modulation due to the sine wave, the spectrum (1) reduces to

$$W(f) = \frac{\hat{E}_0^2}{2} \sum_{-\infty}^{\infty} J_n(b)^2 \delta(f - nf_0), \quad (8)$$

where now there are $(2n + 1)$ sidebands located at frequencies $\pm nf_0$ about the "carrier" f_c $(f = 0)$. The modulation presents a discrete spectrum, which may be broad enough but unfortunately is not sufficiently uniform for barrage jamming. The waveform in the receiver is insufficiently complex and is amplitude-limited.

[a] Some curves illustrating $W(f)$ are given in reference 525.

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Alone it is not satisfactory; but it may be an essential feature, in conjunction with various types of noise modulation, in providing a successful barrage.

In any type of frequency modulation by a sine wave (or any other kind of nonrandom, periodic waveform such as square or sawtoothed waves), there are definite limits on the value of b: if b is too large, "holes" (in time, but not in frequency) will appear in the pattern on the screen, through which the pip will show; if b is too small, there is essentially only one carrier, the original one, and the characteristic features of the frequency modulation are lost.

Case IV: Frequency or Phase Modulation by Noise with Frequency Modulation by a Sine Wave. When the noise band has the spectral shapes considered in Case I, we obtain for the output spectrum

$$W(f) = \frac{\hat{E}_0^2}{2f_s}\left\{\frac{1}{2}\sum_{-\infty}^{\infty} J_n(b)^2\left[\sum_{m=0}^{\infty}(-1)^m d_m \cdot \left(\phi^{(2m)}\left(\frac{nf_0+f}{f_s}\right)+\phi^{(2m)}\left(\frac{nf_0-f}{f_s}\right)\right)\right]\right\}. \quad (9)$$

This shows that about each of the sidebands (frequency nf_0) produced by the sinusoidal frequency modulation there exists a spectral distribution due to the noise. The superposition of these elementary distributions produces the overall spectrum, whose shape may thus be observed to depend noticeably on the modulation index b. As far as uniformity is concerned, best results may occur for values of b between 15 and 25, approximately; this method may be quite effective, as all the energy available for jamming is in the sidebands. There may be, however, a ceiling to the pattern on the screen above which the pip is discernible, unless the sweep rate f_0 is greater than about two or three times the receiver bandwidth.

Case V: Amplitude Modulation by Noise with Frequency Modulation by a Sine Wave. Here the continuous portion of the output spectrum is

$$W(f) = \frac{\gamma^2}{4}\sum_{-\infty}^{\infty} J_n(b)^2 W_A(f). \quad (10)$$

It must be remembered that the complete spectrum includes the carrier energies, mathematically in the form of δ functions superimposed on the sideband spectra. A broad composite spectrum is the result, though not so uniform a one as in Case IV, since the various carriers, or sinusoidal frequency-modulation sidebands, produce peaks in the otherwise uniform spectrum. Best results with regard to spectrum uniformity and avoidance of holes should be obtained for values of b which lie roughly in the range 15 to 25. The ratio of sideband to total energy is limited at best (in the case of extreme clipping) to 1:2, and hence more power will be required for jamming than in Case IV. However, not all the carrier energy should be considered as wasted, since there is (so to speak) a carrier for every channel, which may in certain cases add to the jamming effectiveness. An effect in the other direction is the possibility of a ceiling, because of the fact that we are using amplitude-limited or highly clipped noise. It is estimated that this effect becomes quite pronounced when the receiver width is comparable to the barrage width, but for small receiver-to-barrage width ratios it should be negligible. This type of modulation and that of Case IV seem to be the most promising of the five methods examined, in the light of the above work. Table 1 compares the various types of modulation. Figure 1 illustrates Cases I to IV in a qualitative manner.

TABLE 1. Qualitative comparison of jamming modulations.

Types of modulation	Relative spectral uniformity	Relative spectral width	Relative carrier wastage	Relative overall desirability
I FM or PM by noise	Fair	Fair	None	Fair
II AM by noise	Good	Fair	Considerable	Fair
III FM by sine wave	Poor	Good	None	Poor
IV FM or PM by noise, with FM by sine wave	Good	Good	None	Good
V AM by noise, with FM by sine wave	Good	Good	Some	Good

Experimental work,[b] carried out contemporaneously with these studies, tended to confirm the estimates of the theory. The addition of the frequency modulation by sine wave, however, was not so much of an improvement as had been

[b] See Section 13.2.3, and references 551, 563, 569, 573, 578, and 584. A detailed summary of this experimental work from the radio countermeasures [RCM] point of view is given in reference 746.

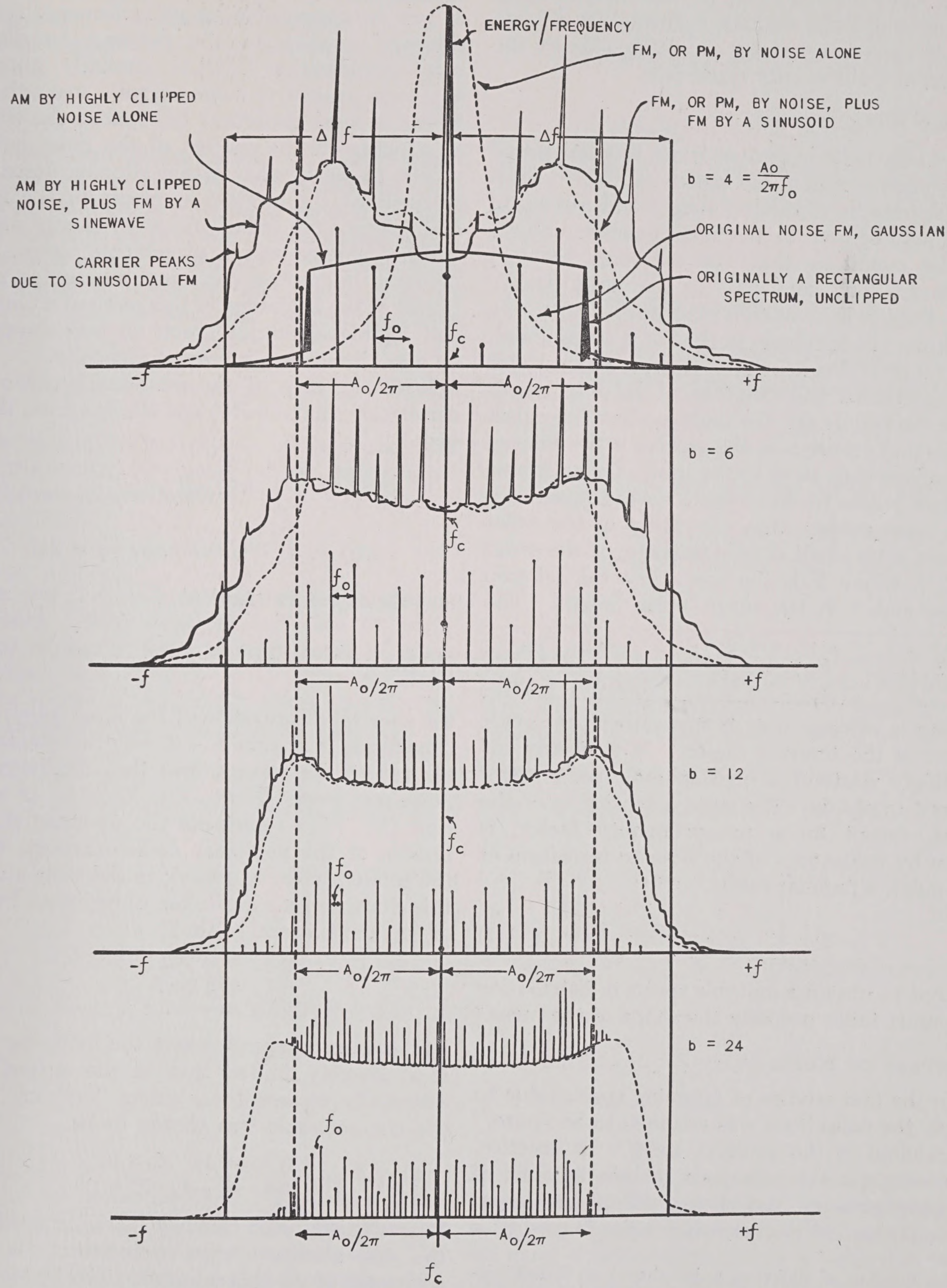


FIGURE 1. Noise modulation spectra with sinusoidal frequency modulation.

[redacted]

hoped, one difficulty being the technical problem of providing large frequency deviations of, say, two or more megacycles on either side of the carrier, at a sufficiently rapid rate.

Pulsed Signals

Not only noise in various forms was considered as a jamming signal, but pulses as well.[528] Such pulses, possibly of random height and spacing in time, may be used to modulate a carrier, subject to the condition that the intervals between pulses are long compared to the pulse length. Thus there is little overlapping, and, analytically speaking, the spectrum is that of a single pulse. The range of frequencies covered is of the order of magnitude of the reciprocal of the pulse length (time duration); and the more random the pulses in size and occurrence, the greater is the efficacy of the jamming, until in the limit of overlapping random pulses we have again an unclipped random noise wave. One advantage of the pulse system is its small carrier wastage, of the order of $\overline{T}/\overline{\tau}$, where $\overline{T}$ is the mean interval between pulses and $\overline{\tau}$ is the mean pulse length. The system is efficient only if rms rather than peak power is the limiting factor. It is clearly exceedingly wasteful if high sporadic peak power is hard to obtain. The energy density ϵ_ν of the pulse, except for a proportionality factor, is given by the square of the Fourier transform of the pulse, a familiar result:

$$\epsilon_\nu = 2\left|\int_{-\infty}^{\infty} f(t)e^{-2\pi\nu it}dt\right|^2, \qquad (11)$$

so that to obtain a suitable spectral distribution one must tailor properly the shape of the pulse.[c]

Clipping of Noise

In the first studies of jamming spectra due to noise, the noise itself was assumed to be "pure," or random in the gaussian sense. In practice, however, there is always a certain amount of clipping present—the slicing off of the larger noise peaks. Moreover, when noise is used as a modulating wave, heavy clipping is necessary to put an appreciable amount of energy in the sideband relative to the carrier. In direct-noise amplification (DINA), similarly, clipping is always present to some degree. Accordingly, it was deemed important to examine the effects of clipping on the spectra of the noise output waves, to see to what extent clipping destroyed or modified the original spectrum of the noise and whether the (relative) loss of energy due to spectral change was a prohibitive factor, particularly in barrage jamming, where (as mentioned at the beginning of this section) a uniform and high-level output spectrum was shown to be a minimum requirement for success.

With the help of the relations between the correlation function $R(t)$ and the spectrum $W(f)$, viz:

$$W(f) = 4\int_0^\infty R(t)\cos\omega t dt;$$

$$R(t) = \int_0^\infty W(f)\cos\omega t df, \quad \omega = 2\pi f, \qquad (12)$$

and the expression for $R(t)$

$$R(t) = \frac{1}{2\pi(1-r^2)^{\frac{1}{2}}}\int_{-\infty}^{\infty}dX\int_{-\infty}^{\infty}dYf(X)f(Y)e^{-(X^2+Y^2-2rXY)/2(1-r^2)}, \qquad (13)$$

the spectral distribution of the noise wave, X at time t_0 and Y at time $t_0 + t$, may be determined, subject to the assumptions that originally the noise was pure. Here $X^2 = Y^2 = 1$. In equation (13), $f(X)$ represents the dynamic characteristic of the nonlinear device through which the random noise is passed; in the early studies, this characteristic was taken to be linear, limited at top and bottom, so that

$$\begin{aligned} f(X) &= X \text{ for } |X| < b, \\ f(X) &= b \text{ for } X \geqq b, \\ f(X) &= -b \text{ for } X \geqq -b. \end{aligned} \qquad (14)$$

For extreme clipping, where the incoming wave is so severely limited that in the output it is essentially square (i.e., either "on" or "off") the characteristic was chosen to be

$$\begin{aligned} f(X) &= 1, \quad X > 0, \\ f(X) &= -1, \quad X < 0. \end{aligned} \qquad (15)$$

It was chiefly with this latter case in mind that the first studies[547] were undertaken. A short treatment of the characteristic given by equation (14) was carried through, enough to complete

[c] A number of different pulse shapes and their corresponding energy densities are illustrated on page 5 of reference 528.

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the data for Figures 2 to 4; a more comprehensive study[589, 596] is discussed below.

From equation (15) the correlation function becomes

$$R(t) = \frac{2}{\pi} \sin^{-1} r(t). \tag{16}$$

Two cases are distinguished: (1) Dina, where the input noise to be clipped is confined to a band narrow compared with its mean frequency, and there is no carrier; and (2) amplitude modulation of a carrier modulated by random noise, the r-f part of which is then passed into the "clipper." In the first case the output correlation is

$$R(t) = \frac{2}{\pi} \sin^{-1} [r_0(t) \cos \omega_c t], \tag{17}$$

where $r_0(t)$ is the correlation of the noise, and f_c is the central frequency of the noise band. For the second case we find

$$R(t) = \frac{2}{\pi} \cos \omega_c t \ \sin^{-1} r_0(t), \tag{18}$$

where now f_c may be interpreted as the carrier frequency. Both case (1) and case (2) were treated explicitly for a uniform band of noise extending from $-\omega_a$ to $+\omega_a$. The resulting spectra appear in the form of zones, four for the approximation used. We have for case (1):

$$W(f)_2 = 2\pi E_\omega = \frac{2}{\omega_a} (1.1928 - 0.05785k^2 + 1.579 \cdot 10^{-3}k^4 - 1.94 \cdot 10^{-5}k^6), \quad |k| < 1, \tag{20a}$$

$$= \frac{2}{\omega_a} (0.2533 - 0.1174k - 6.59 \cdot 10^{-3}k^2 + 7.138 \cdot 10^{-3}k^3 + 1.334 \cdot 10^{-4}k^4 - 2.035 \cdot 10^{-4}k^5 + 1.454 \cdot 10^{-5}k^6), \quad 1 < |k| < 3, \tag{20b}$$

$$= \frac{2}{\omega_a} (0.13012 - 6.820 \cdot 10^{-2}k + 5.5 \cdot 10^{-4}k^2 + 6.4 \cdot 10^{-3}k^3 - 1.637 \cdot 10^{-3}k^4 + 1.63 \cdot 10^{-4}k^5 - 5.814 \cdot 10^{-6}k^6), \quad 3 < |k| < 5, \tag{20c}$$

$$= \frac{2}{\omega_a} (8.02 \cdot 10^{-3} + 2.950 \cdot 10^{-2}k - 2.875 \cdot 10^{-2}k^2 + 1.031 \cdot 10^{-2}k^3 - 1.832 \cdot 10^{-3}k^4 + 1.63 \cdot 10^{-4}k^5 - 5.814 \cdot 10^{-6}k^6), \quad 5 < |k| < 7, \tag{20d}$$

where again $E_\omega = 0$, for $|k| > 7$, unless more terms in the original series for E_ω are employed. Here the expression above for $W(f)_2$ is 18 per cent too small. This, however, is not too serious

$$W(f)_1 = 2\pi E_\omega = \frac{2}{\omega_a} (1.134 - 0.0410k^2 + 9.552 \cdot 10^{-4}k^4 - 1.060 \cdot 10^{-5}k^6), \quad |k| < 1, \tag{19a}$$

$$= \frac{2}{\omega_a} (0.1799 - 0.0890k - 1.20 \cdot 10^{-3}k^2 + 4.51 \cdot 10^{-3}k^3 + 1.26 \cdot 10^{-5}k^4 - 1.113 \cdot 10^{-4}k^5 + 7.89 \cdot 10^{-6}k^6), \quad 1 < |k| < 3, \tag{19b}$$

$$= \frac{2}{\omega_a} (0.0808 - 4.492 \cdot 10^{-2}k + 2.61 \cdot 10^{-3}k^2 + 3.208 \cdot 10^{-3}k^3 - 8.809 \cdot 10^{-4}k^4 + 8.91 \cdot 10^{-5}k^5 - 3.18 \cdot 10^{-6}k^6), \quad 3 < |k| < 5, \tag{19c}$$

$$= \frac{2}{\omega_a} (4.39 \cdot 10^{-3} + 1.613 \cdot 10^{-2}k - 1.571 \cdot 10^{-2}k^2 + 5.65 \cdot 10^{-3}k^3 - 1.003 \cdot 10^{-3}k^4 + 8.91 \cdot 10^{-5}k^5 - 3.18 \cdot 10^{-6}k^6), \quad 5 < |k| < 7, \tag{19d}$$

and $E_\omega = 0$ for $|k| > 7$, unless more than four terms of the series are used. The series (19a) to (19b) are in deficit from the true value by about 6 per cent, if attention is confined to the spectrum $W(f)_1$ about the first harmonic of f_c. For case (2) the results take the form:

an error if one is interested primarily in the spectral distribution for $|k| \leqq 1$, corresponding to the width of the noise band before clipping, for most of the omitted energy is located outside the band. In other words, the percentage error is here least for $k = 0$, about 6 per cent, out to

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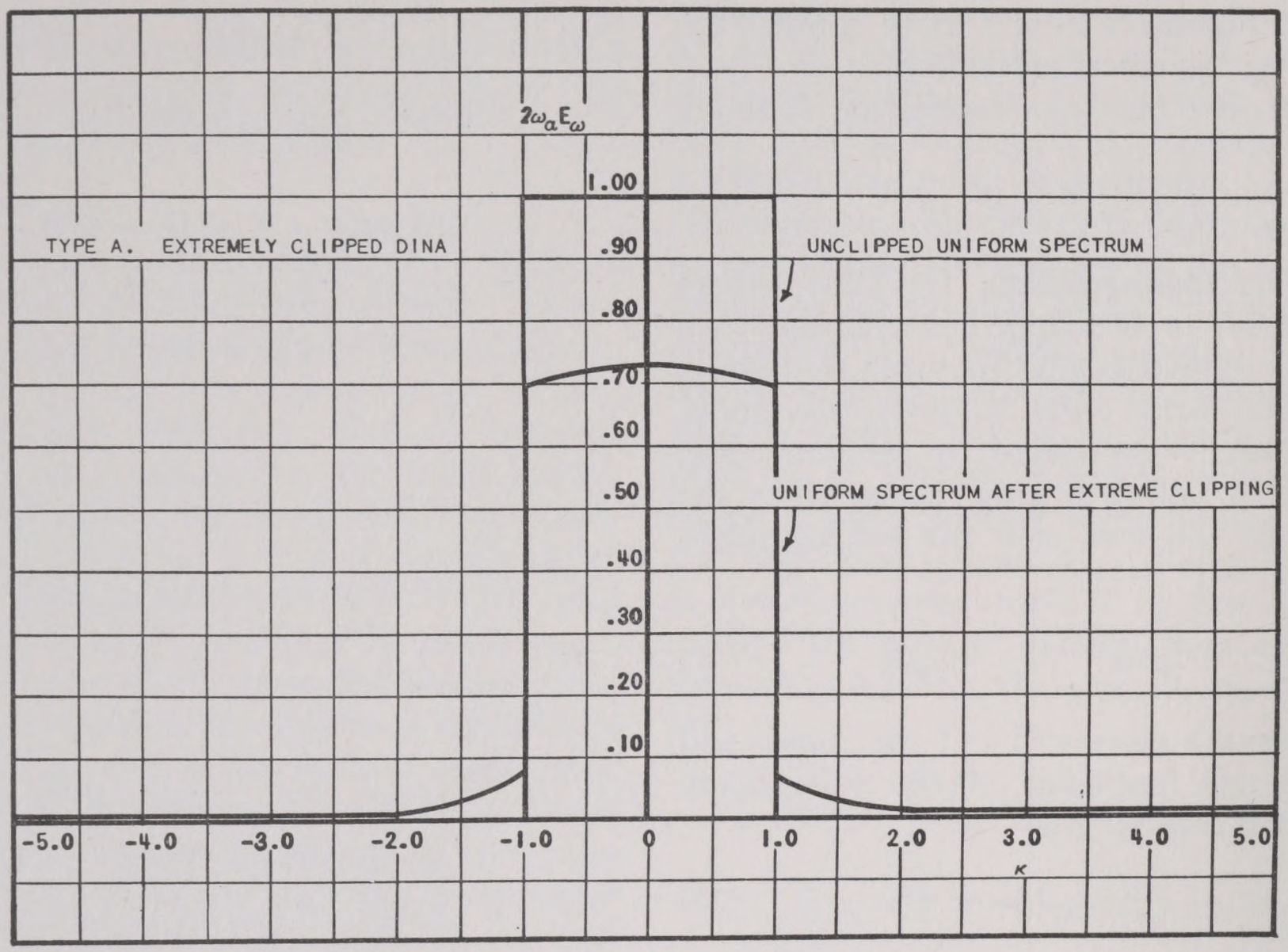


FIGURE 2. Noise spectrum of Dina after extreme clipping.

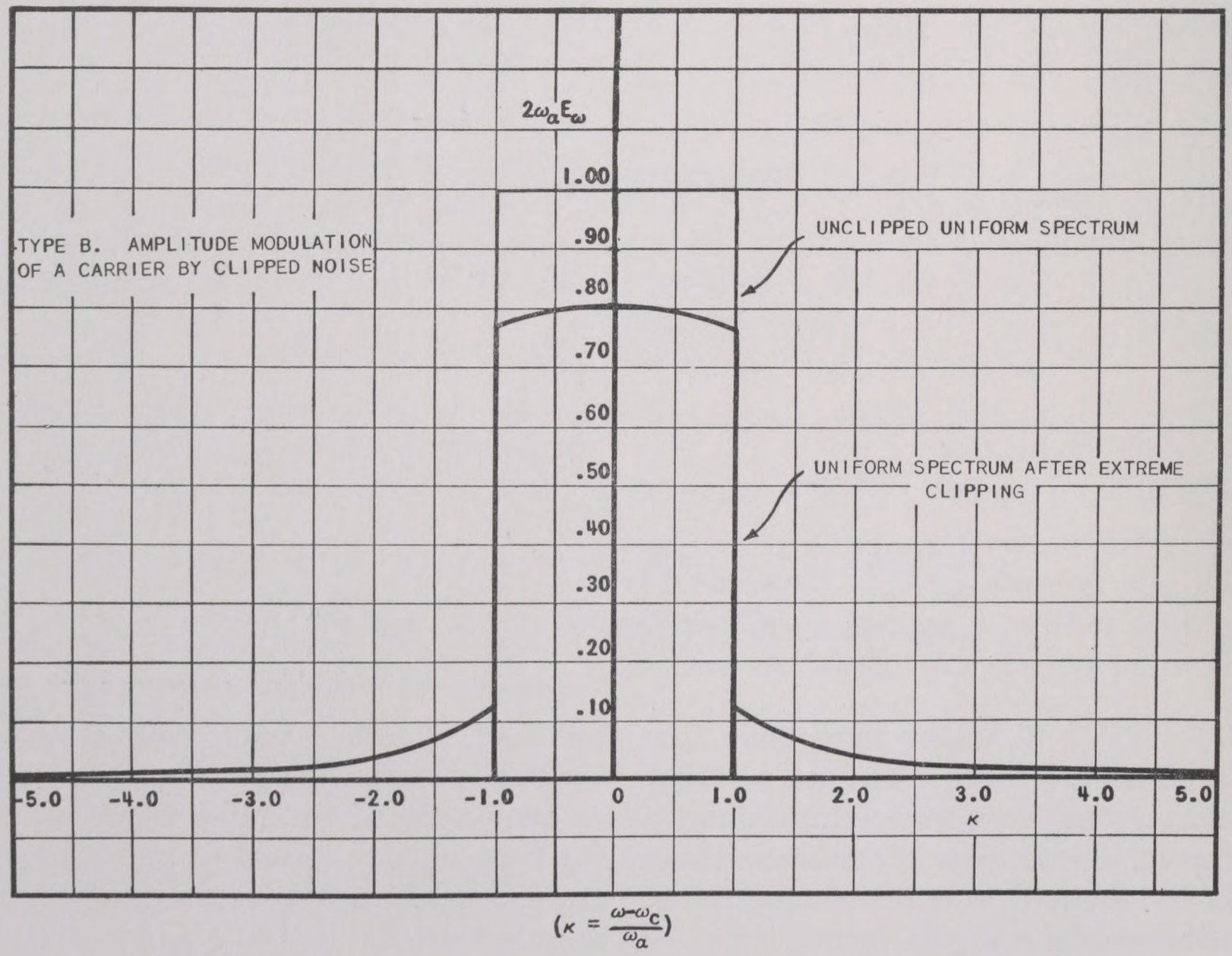


FIGURE 3. Spectrum of a carrier amplitude modulated by extremely clipped noise.

$|k| = 1$, and increases for larger values of $|k|$. The spectra of equations (19) and (20) are illustrated in Figures 2 to 4. Clipping at an intermediate level is also shown—see equation (14). This particular study also included "gaussian" and "optical" spectra.[d]

If the clipping is not done below the rms level before limiting (equivalent to clipping at about 1.4 times the rms level after clipping), there is practically no distortion of the spectrum. Even in the case of extreme clipping or "superclipping" the wastage of power due to spoiling of the spectrum's uniformity is small, amounting to only 31 per cent in case (1) and 24 per cent in case (2). Of the 31 per cent loss in (1), 19 per cent is due to production of bands about harmonics of the central frequency. Corresponding harmonics are absent in (2). *Clipping is beneficial in either (1) or (2) from the standpoint of reducing peak power requirements. In addition, for (2) it materially diminishes the wastage of power in the carrier frequency.* These facts are demonstrated for an originally uniform noise spectrum in Tables 2 and 3. The bottleneck factor in Table 2 is the spectral ordinate at $|k| = 1$ (see Figures 2 to 4). The ratio of effective energy to total mean energy is obtained by dividing the bottleneck factor by $1 + \rho$, where ρ is the ratio of carrier to sideband energy. The

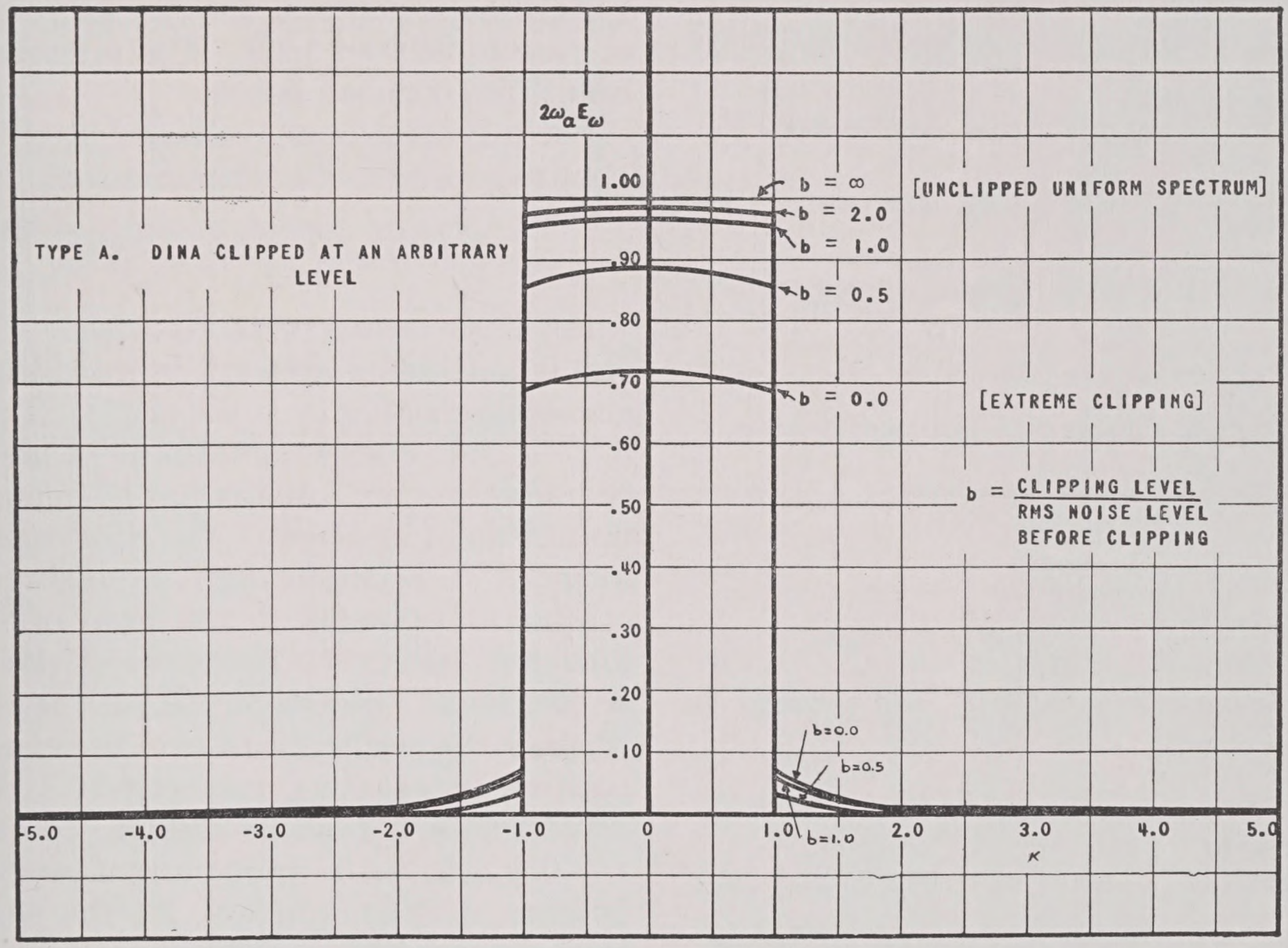


FIGURE 4. Spectra of Dina after clipping at arbitrary levels.

ratio of effective energy to peak energy is found by dividing the bottleneck factor by $b^2/R(0)$, where $R(0) = b^2 - \left(\frac{2}{\pi}\right)^{\frac{1}{2}} be^{\frac{-b^2}{2}} + (1-b^2)\,\Theta(b/\sqrt{2})$ and Θ is the familiar error integral $\frac{2}{\pi^{\frac{1}{2}}}\int_0^x e^{-y^2}dy$.

Table 3 was drawn up similarly for case (2). The same definitions apply here as in Table 2. The peak power, the power in the noise sidebands, and the power in the carrier are proportional to $4b^2$, $R(0)$, and b^2 respectively; ρ is then $b^2/R(0)$. In case (1) there is no carrier, and the

[redacted]

[d]The effects of clipping on these can be observed in Figures 7 to 10 of reference 547.

ratio of peak power to rms noise power is $b^2/R(0)$, instead of $4b^2/R(0)$ as found for case (2).

TABLE 2. Effect of clipping on Dina noise—Case (1).

	Extreme clipping				No clipping
$\frac{\text{Clipping amplitude}}{\text{Original rms amp.}} = b$	0	0.5	1.0	2.0	∞
$\frac{\text{Clipping amplitude}}{\text{Rms amp. after clipping}}$	1.00	1.17	1.39	2.09	∞
Bottleneck factor	0.69	0.86	0.95	0.97	1
Fraction of the energy in harmonic zones	0.19	0.08	0.03	0.005	0
$\frac{\text{Effective energy}}{\text{Total mean energy}}$	0.69	0.86	0.95	0.97	1
$\frac{\text{Effective energy}}{\text{Peak energy}}$	0.69	0.63	0.49	0.22	0

TABLE 3. Effect of clipping on a noise-modulated carrier—Case (2).

	Extreme clipping				No clipping
$\frac{\text{Clipping amplitude}}{\text{Original rms amp.}} = b$	0	0.5	1.0	2.0	∞
$\frac{\text{Clipping amplitude}}{\text{Rms amp. after clipping}}$	1.00	1.17	1.39	2.09	∞
Bottleneck factor	0.76	0.88	0.95	0.98	1
Ratio of sideband to carrier energy $= 1/\rho$	1.00	0.74	0.52	0.23	0
$\frac{\text{Effective energy}}{\text{Total rms energy}}$	0.38	0.37	0.32	0.18	0
$\frac{\text{Effective energy}}{\text{Peak energy}}$	0.19	0.16	0.12	0.06	0

It is to be observed once again that the effectiveness of clipped noise in jamming a receiver is not determined from a study of the spectrum of the transmitted wave alone. For, qualitatively, if the receiver breadth is small compared with the noise band, the received disturbance will have the same type of gaussian fluctuation, and hence the same effectiveness, as unclipped noise with the same spectral distribution. But if the receiver is comparable with the noise band in width, there will be a tendency, as a result of the clipping, for a ceiling in the resultant deflection of the recording device, and, under these conditions, the utility of clipped noise for jamming is materially diminished.

RECTIFICATION OF NOISE

The first treatment[547] of limited noise dealt only with symmetrical clipping by a linear characteristic. The study was extended to the more general cases of clipping due to arbitrary cutoff and saturation levels[589,590] in connection with the modification of the spectral output of various noise sources, described from this point of view in Section 6.2.3. The principal analytic results are outlined below.

For a general input voltage $V(t)$ entering the nonlinear device, the output current is given by

$$I(t) = \frac{1}{2\pi}\int_C f(iz)e^{iV(t)z}dz, \tag{21}$$

where C is a contour extending from $-\infty$ to $+\infty$ and is indented downward in a semicircle about a possible singularity at the origin. The function $f(iz)$ is the Fourier transform of the detector characteristic and usually has a simple pole or a branch point at $z = 0$. The convergence of the integral of equation (21) is unaltered if the contour is extended in the form of an infinite semicircle either in a counterclockwise (positive) or clockwise (negative) sense, depending on whether the coefficient of iz in the exponential is positive or negative, respectively. When C is traversed in a positive fashion, the residue at $z = 0$ yields the output current as the desired function of $V(t)$, whereas, for the negative circuit, $I(t)$ vanishes. In this way one is able to distinguish between the cutoff and transmission states of the apparatus.

If the correlation function $R(t)$ of the output is known, the energy spectrum is found at once.[e] Following the method suggested by Rice,[835] we obtain finally the spectrum

$$W(f) = \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} h_{0,n}^2 C_{0,n}(f), \tag{22}$$

where

$$C_{0,n}(f) = 4\int_0^{\infty} \psi(t)^n \cos \omega t dt, \tag{23}$$

and

$$h_{0,n} = \frac{1}{2\pi}\int_C z^n f(iz)e^{-\psi(0)z^2/2}dz. \tag{24}$$

[e] See equation (12); also see page 16 of reference 547.

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The expression $\psi(t)$ is the correlation function of the input disturbance, given by

$$\psi(t) = \int_0^\infty w(f) \cos \omega t df, \quad \omega = 2\pi f, \tag{25}$$

where $w(f)$ is the spectrum of the incoming wave. The mean-square input noise voltage $\psi(0) \equiv \psi$ is

$$\psi(0) = \int_0^\infty w(f) df. \tag{26}$$

Then the correlation function of the output wave is

$$R(t) = \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} h_{0,n}^2 \psi(t)^n. \tag{27}$$

The d-c and continuum powers become

$$W_{d-c} = h_{0,0}^2,$$

$$W_c = \sum_{n=1}^{\infty} \frac{(-1)^n \psi(0)^n}{n!} h_{0,n}^2. \tag{28}$$

An alternative form for the total power output is

$$R(0) = \frac{1}{(2\pi)^{\frac{1}{2}}} \int_{-\infty}^{\infty} I\,(\psi^{\frac{1}{2}} x)^2\, e^{-x^2/2}\, dx,$$
$$W_c = R(0) - h_{0,0}^2. \tag{29}$$

Three specific dynamic characteristics were examined. They are illustrated in Figure 5.

for which we obtain

$$h_{0,0} = -\frac{1}{2}\beta\psi^{\frac{1}{2}} [\bar{C}\,(\Theta_c - 1) - \bar{b}_0\,(\Theta_{b_0} - 1) + 2\,(\phi_c - \phi_{b_0})], \tag{31a}$$

$$h_{0,1} = -\frac{1}{2}\beta i\,[\Theta_c - \Theta_{b_0}], \tag{31b}$$

$$h_{0,n} = \beta\,(-1)^{n+2\,/2}\,\psi^{1-n\,/2}\,[\phi_c^{(n-2)} - \phi_{b_0}^{(n-2)}], \quad n = 2, 4, 6 \cdots \tag{31c}$$

$$h_{0,n} = \beta i\,(-1)^{n+3\,/2}\,\psi^{1-n\,/2}\,[\phi_c^{(n-2)} - \phi_{b_0}^{(n-2)}], \quad n = 3, 5, 7 \cdots \tag{31d}$$

where the following abbreviations are indicated:

$$b_0 \equiv \frac{b_0}{\psi^{\frac{1}{2}}};\ C = \frac{C}{\psi^{\frac{1}{2}}};\ \Theta_{b_0} \equiv \Theta\left(\frac{b_0}{(2\psi)^{\frac{1}{2}}}\right);\ \Theta \equiv \Theta\frac{C}{(2\psi)^{\frac{1}{2}}}, \tag{32a}$$

$$\phi_{b_0}^{(j)} \equiv \phi^{(j)}\left(\frac{b_0}{\psi^{\frac{1}{2}}}\right);\ \phi^{(j)}\left(\frac{C}{\psi^{\frac{1}{2}}}\right). \tag{32b}$$

The functions Θ and $\phi^{(j)}$ are defined as

$$\Theta\,(x_0) \equiv \frac{2}{\pi^{\frac{1}{2}}} \int_0^{x_0} e^{-y^2}\, dy,$$
$$\Theta\,(x_0) = -\Theta(-x_0),$$
$$\phi^{(j)}(x_0) \equiv \frac{d^{(j)}}{dx^j} \frac{e^{-x^2/2}}{(2\pi)^{\frac{1}{2}}}\Bigg|_{x=x^0} = \frac{(-1)^j H_j(x_0) e^{-x_0^2/2}}{(2\pi)^{\frac{1}{2}}}, \tag{33}$$

with $H_j(x_0)$ an Hermitian polynomial of the jth order. The total power output is in this case

$$R(0) = \frac{1}{2}\beta^2\psi\,[(\bar{C} - \bar{b}_0)^2 + (1 + 2\bar{C}\bar{b}_0 - \bar{C}^2\Theta_c) - (1 + \bar{b}_0^2)\Theta_{b_0} + 4\bar{b}_0\phi_c + 2\phi_c^{(1)} + 2\phi_{b_0}^{(1)}]. \tag{34}$$

Here b_0 is the cutoff voltage, measured from the operating point, and C is a voltage, measured as indicated in Figure 5; β, γ, λ are tube constants with the dimensions of mhos.

Linear Rectifier. For the biased and saturated linear rectifier, we have

$$f(iz)_e = \frac{\beta(e^{-ib_0 z} - e^{-iCz})}{(iz)^2} \tag{30}$$

Type A Quadratic Rectifier. For the biased, saturated type A quadratic response, illustrated in Figure 5, one has

$$f(iz)_{q-A} = 2\gamma^2\left[\frac{e^{-ib_0 z} - e^{-iCz}}{(iz)^3} + (b_0 - C)\ \frac{e^{-iCz}}{(iz)^2}\right], \tag{35}$$

from which it follows, in conjunction with equation (24), that

$$h_{0,0} = -\gamma^2\psi\left[\frac{(\bar{b}_0^2 + 1)}{2}(\Theta_{b_0} - 1) + \frac{(\bar{C}^2 - 2\bar{b}_0\bar{C} - 1)}{2}(\Theta_c - 1) + \bar{C}\phi_c + \bar{b}_0\,(\phi_{b_0} - 2\phi_c)\right], \tag{36a}$$

$$h_{0,1} = -i\gamma^2\psi^{\frac{1}{2}}\,[\bar{b}_0\,(\Theta_{b_0} - \Theta_c) + 2\,(\phi_{b_0} - \phi_c)], \tag{36b}$$

$$h_{0,2} = \gamma^2\,[\,\Theta_{b_0} - \Theta_c + 2(\bar{C} - \bar{b}_0)\,\phi_c\,], \tag{36c}$$

$$h_{0,n} = 2i\gamma^2\,(-1)^{n-3\,/2}\,\psi^{2-n\,/2}\,[\phi_{b_0}^{(n-3)} - \phi_c^{(n-3)} - (\bar{b}_0 - \bar{C})\,\phi_c^{(n-2)}], \quad n = 3, 5, 7 \cdots, \tag{36d}$$

$$h_{0,n} = 2\gamma^2\,(-1)^{n-2\,/2}\,\psi^{2-n\,/2}\,[\phi_{b_0}^{(n-3)} - \phi_c^{(n-3)} - (\bar{b}_0 - \bar{C})\,\phi_c^{(n-2)}], \quad n = 4, 6, 8, \cdots. \tag{36e}$$

For the total power output we have the closed expression, analogous to equation (34):

$$R(0) = \gamma^4\psi^2\left[-\frac{(\bar{C}-\bar{b}_0)^4}{2}(1-\Theta_c) + \frac{(3+6\bar{b}_0^2+\bar{b}_0^4)}{2}(\Theta_c-\Theta_{b_0}) - (\bar{b}_0^3+5\bar{b}_0)\,\phi_{b_0} - (\bar{C}^3+3\bar{C}+6\bar{b}_0^2\bar{C}-4\bar{C}^2\bar{b}_0-8\bar{b}_0-4\bar{b}_0^3)\,\phi_c\right], \quad C \geqq b_0. \tag{37}$$

Type B Quadratic Rectifier. For type B quadratic detector, shown in Figure 5, we may write

$$f(iz)_{q-B} = 2\lambda^2\left[\frac{e^{-ib_0z}+e^{-i(2C-b_0)z}-2e^{-iCz}}{(iz)^3}\right], \quad C \geqq b_0. \tag{38}$$

The $h_{0,n}$'s in this instance have the forms

$$h_{0,0} = -\lambda^2\psi\left[\frac{\bar{b}_0^2+1}{2}(\Theta_{b_0}-1) + \bar{b}_0\,\phi_{b_0} + \left(\frac{(2\bar{C}-\bar{b}_0)^2+1}{2}\right)(\Theta_{2C-b_0}-1) + (2\bar{C}-\bar{b}_0)\,\phi_{2C-b_0} - 2\left(\frac{\bar{C}^2+1}{2}\right)(\Theta_c-1)+2\phi_c\right], \tag{39a}$$

$$h_{0,1} = -i\lambda^2\psi^{\frac{1}{2}}[\bar{b}_0(\Theta_{b_0}-1)+2\phi_{b_0}+(2\bar{C}-\bar{b}_0)(\Theta_{2C-b_0}-1)+2\phi_{2C-b_0}-2\bar{C}(\Theta_c-1)-4\phi_c], \tag{39b}$$

$$h_{0,2} = \lambda^2[\Theta_{b_0}+\Theta_{2C-b_0}-2\Theta_c], \tag{39c}$$

$$h_{0,n} = 2i\lambda^2(-1)^{n-3/2}\psi^{2-n/2}[\phi_{b_0}{}^{(n-3)}+\phi_{2C-b_0}{}^{(n-3)}-2\phi_c{}^{(n-3)}],\ n=3,5,7,\cdots \tag{39d}$$

$$h_{0,n} = 2\lambda^2(-1)^{n-2/2}\psi^{2-n/2}[\phi_{b_0}{}^{(n-3)}+\phi_{2C-b_0}{}^{(n-3)}-2\phi_c{}^{(n-3)}],\ n=4,6,8\cdots \tag{39e}$$

where the additional abbreviations

$$\phi^{(j)}{}_{2C-b_0} \equiv \phi^{(j)}\left(\frac{2C-b_0}{\psi^{\frac{1}{2}}}\right), \qquad \Theta_{2C-b_0} \equiv \Theta\left(\frac{2C-b_0}{(2\psi)^{\frac{1}{2}}}\right) \tag{40}$$

have been made. The total output power $R(0)$ here takes the form

$$R(0) = \frac{\lambda^4\psi^2}{2}[\,P_1\Theta_{2C-b_0} - P_2\Theta_c - P_3\Theta_{b_0} + 2P_4\phi_{2C-b_0} + 2P_5\phi_c - 2P_6\phi_{b_0} + 4(\bar{C}-\bar{b}_0)^4\,], \tag{41}$$

where now

$$P_1 = 16\bar{C}^3\bar{b}_0 - 28\bar{C}^2\bar{b}_0^2 + 16\bar{C}\bar{b}_0^3 - 3\bar{b}_0^4 + 20\bar{C}^2 - 16\bar{C}\bar{b}_0 + 2\bar{b}_0^2 + 3, \tag{42a}$$

$$P_2 = 4\bar{C}^4 - 4\bar{C}^2\bar{b}_0^2 - 4\bar{b}_0^2 + 20\bar{C}^2 - 16\bar{C}\bar{b}_0, \tag{42b}$$

$$P_3 = \bar{b}_0^4 + 6\bar{b}_0^2 + 3, \tag{42c}$$

$$P_4 = 3\bar{b}_0^3 - 5\bar{b}_0 + 8\bar{b}_0\bar{C}^2 - 10\bar{b}_0^2\bar{C} + 10\bar{C}, \tag{42d}$$

$$P_5 = 4(4\bar{b}_0 - 4\bar{C} + \bar{b}_0^2\bar{C} - \bar{C}^3), \tag{42e}$$

$$P_6 = \bar{b}_0^3 + 5\bar{b}_0. \tag{42f}$$

Conclusions. From these general results, equations (22) to (42f), the distributions of the power and the spectra were determined for a variety of input spectra and operating conditions; i.e., values of b_0 and C. The theory of extreme or superclipping was also generalized for the previous work[547] to give, for the correlation function of the highly clipped output,

$$R(t) = B(\epsilon)\left[\left(\frac{1-\Theta_{b_0}}{2}\right)^2 + \sum_{n=1}^{\infty}\frac{[\phi_{b_0}{}^{(n-1)}]^2 r(t)^n}{n!}\right], \quad 0 < \epsilon << 1, \tag{43}$$

where B is $\epsilon^2\beta^2$, $\epsilon^4\gamma^4$ and $4\epsilon^4\lambda^4$ for the linear type A and type B devices, respectively. Here $r(t) \equiv \psi(t)/\psi(0)$. The total output power and that in the continuum are

$$\therefore \quad R(0) \doteq B\left(\frac{1-\Theta_{b_0}}{2}\right), \qquad W_c \doteq B\left(\frac{1-\Theta_{b_0}{}^2}{4}\right). \tag{44}$$

A few general observations are pertinent. (1) The output power is independent of the spectral shape of the input disturbance,[f] and (2) clipping, whether at the "top" or "bottom" of the wave, always spreads the spectrum. There are other interesting results that are more readily considered in Section 6.2.3, in which specific application of the above analysis to the problem of distorting the output spectrum of various noise sources is given.

[f] See equation (4.9-19) of reference 835.

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6.2.2 Visibility of Signals through Noise

The general problem investigated in Section 6.2.1 is concerned with the spectral characteristics of broadcast noise, or noise-modulated waves, primarily from the RCM viewpoint. A considerable amount of work was done also on the general problem of jamming effectiveness from a somewhat different outlook; specifically, on the theory of the nonlinear operation of various devices upon a signal in the presence of noise. The device in question is the second detector of the receiver being jammed. This subject has been approached with two separate but allied ends in view. The first, of course, is the effectiveness of RCM in obliterating a signal viewed on the oscilloscope screen or perceived by other methods, and the second concerns the efficacy of antijamming [AJ] measures in nullifying enemy interference. It was realized early in the program that a study of the spectrum of the transmitted wave was not enough; consequently, a general theoretical examination of a number of methods of detecting signals in the presence of noise was started in the summer of 1943.

Rectification of a Modulated Signal in Noise

Before it can be determined to what extent noise inhibits the reception of signals, a theory must be constructed capable of handling at least the more important aspects of the detection of a *modulated* signal in the presence of noise by (1) a linear rectifier, and (2) a quadratic rectifier, since these two dynamic characteristics are sufficient approximations to a large number of practical responses. The correlation function of the output of a general nonlinear device was shown to be[389]

$$R(t) = \overline{G\,(t_0, t_0')\;G\,(t_0 + t, t_0' + t)} = \frac{1}{T_0'}\int_0^{T_0'} dt_0' \int_0^{T_0} \frac{dt_0}{T_0}\, R_N\,(t_0', t_0; t), \quad (45)$$

where t_0' applies to the modulation, if any, t_0 to the carrier, and $R_N(t_0,t_0';t)$ is the correlation function of the output after the averaging over the random noise variables has been performed—in the manner, say, of equation (13). The quantities T_0 and T_0' are the periods, respectively, of the carrier and modulation. If the envelope and carrier are uncorrelated, as they usually are, t_0' and t_0 are independent; however, should there exist correlation between envelope and carrier, then t_0' and t_0 would be functionally related.

Now R_N is determined by

$$R_N\,(t_0, t_0'; t) = \int_{-\infty}^{\infty} I\,(X, t_0, t_0')dX \int_{-\infty}^{\infty} \frac{I(Y, t_0+t, t_0'+t)dY}{2\pi\psi\,(1-r^2)^{\frac{1}{2}}}\, e^{-(X^2 + Y^2 - 2rXY)/2\,(1 - r^2)\,\psi}, \quad (46)$$

where $I(X,t_0,t_0')$ is the output current as a function of input voltage at one time t_0, and $I(Y, t_0 + t, t_0' + t)$ is the output at time t later. The quantity $r(t)$ is the correlation of the input noise, and ψ is the mean-square input voltage. Let $f_1 = f_1\,(t_0, t_0')$, $f_a = f_2(t_0 + t, t_0' + t)$ be the periodic part of the incoming signal and noise; then it follows at once from equation (46) specifically for a *biased, linear rectifier* that

$$R_N\,(t_0, t_0'; t) = \frac{\beta^2}{2\pi\psi}\int_{b_0 - f_1}^{\infty} dX \int_{b_0 - f_2}^{\infty} dY\, \frac{(X + f_1 - b_0)\,(Y + f_2 - b_0)}{(1 - r^2)^{\frac{1}{2}}}\, e^{-(X^2 + Y^2 - 2rXY)/2\,\psi\,(1 - r^2)}, \quad (47)$$

where β, as before, is the dynamic transconductance of the tube. For a modulated carrier, one may write

$$f(t) = F(t)\cos\omega_0 t, \quad \omega_0 = 2\pi f_0, \quad (48)$$

with f_0 the carrier frequency and $F(t)$ the envelope. The "discrete," or slowly varying portion of the output may be obtained on setting $t = \infty$ in equation (46) in so far as the more rapidly varying noise is concerned; the result for equation (47) is

$$R_N\,(t_0, t_0'; t)_{\text{discrete}} = \frac{\beta^2}{2\pi\psi}\int_{b_0 - f_1}^{\infty} dX \int_{b_0 - f_2}^{\infty} dY\,(X + f_1 - b_0)\,(Y + f_2 - b_0)\, e^{-(X^2 + Y^2)/2\,\psi} = \overline{(X + f_1 - b_0)_N}\;\overline{(Y + f_2 - b_0)_N}. \quad (49)$$

[redacted]

Then for the biased linear detector the mean area under a cycle of the carrier after rectification is[g]

$$E(t)_{\text{m. area}} = \frac{1}{T_0}\int_0^{T_0}\overline{(X + f_1 - b_0)_N}\, dt_0$$

$$= \frac{\beta}{T_0\sqrt{2\pi\psi}}\int_0^{T_0} dt_0 \int_{b_0 - f(t_0)}^{\infty} [X + f(t_0) - b_0]\, e^{-X^2/2\psi}\, dX. \quad (50)$$

From equation (50) it was also shown that when there is no bias ($b_0 = 0$) the results of North,[836] Goudsmit,[837] and Jordan[838] are equivalent. The expressions are

$E(t)_{\text{m. area}}$

$$= \frac{\beta\psi^{\frac{1}{2}}}{\sqrt{2\pi}}\, e^{-\frac{\lambda}{2}}\left[(1+\lambda)I_0\left(\frac{\lambda}{2}\right) + \lambda I_1\left(\frac{\lambda}{2}\right)\right], \qquad \lambda = \frac{F(t)^2}{2\psi}$$

$$= \frac{\beta\psi^{\frac{1}{2}}}{\sqrt{2\pi}}\, {}_1F_1\left(-\frac{1}{2}; 1; -\frac{F(t)^2}{2\psi}\right), \quad (51)$$

where ${}_1F_1$ is a confluent hypergeometric function, and I_0 and I_1 are modified Bessel functions of the first kind.

For small-signal quadratic rectification, R_N was shown to be[586]

$$R_N(t_0, t_0'; t) = \gamma^4\psi^4(1 + 2r^2 + 4abr + a^2b^2 + a^2 + b^2) + \beta^2\psi(r + ab) + \alpha^2 + \alpha\beta\psi^{\frac{1}{2}}(a + b) + \alpha\gamma^2\psi(2 + a^2 + b^2) + \beta\gamma^2\psi^{3/2}(a + b)(1 + 2r + ab), \quad (52)$$

where

$$a \equiv \frac{F(t_0')\cos\omega_0 t_0}{\psi^{\frac{1}{2}}}, \qquad b \equiv \frac{F(t_0' + t)\cos\omega_0(t_0 + t)}{\psi^{\frac{1}{2}}},$$

and F represents the modulation on the carrier $\cos\omega_0 t$. The quantities α, β, and γ are constants of the dynamic response, which is a general parabola of the form

$$I(t) = \alpha + \beta V(t) + \gamma V(t)^2$$

for *all* values of $V(t)$—this latter on the assumption that the incoming wave is small-signal; that is, that very large amplitudes relative to the transmission portion of the characteristic occur very infrequently. One interesting conclusion of the analysis[585] is that for *half-wave* quadratic

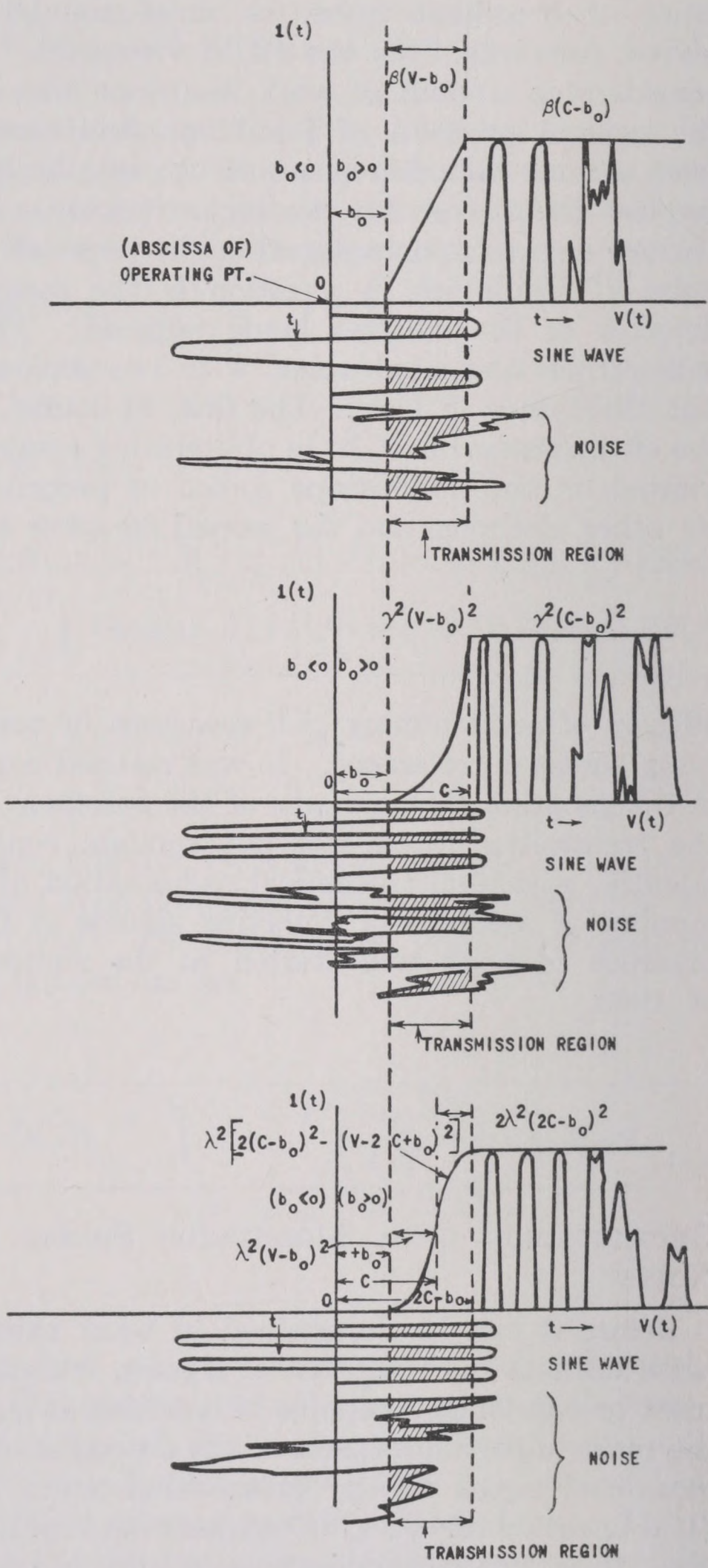


FIGURE 5. Dynamic characteristics of biased saturated linear and quadratic rectifiers.

responses the ratio of the l-f part of the signal (i. e., the envelope) to the l-f noise (without signal) is the same as for full-wave rectification,

[g]It should be noted that in reference 389 equations (10) and (15) to (18) are not correct; one should insert $-b_0$ in the parenthesis $(x + f_1)$, etc.

each diminished by a factor 4 from its value in the latter instance.

Reception of Radar Signals through Noise

The next effort was directed toward a theoretical examination of the relative sensitivity of the perception of radar signals in the presence of noise by visual detection (the A scope), by aural detection (in which one listens to the fundamental or a low harmonic of the prf), and by a meter. The metering scheme may be either aperiodic, where the rectified current is fed directly to a meter with a long time constant, or periodic, where the rectified current is sent through an audio filter tuned to the prf, given a supplementary rectification, and then passed through the meter. The dependence of the sensitivities of the different methods on various relevant parameters was studied in some detail. These parameters included the width and the shape of the i-f response, the pulse length, the prf, and, in aural or meter reception, the duration of the gate, the width of the audio filter, or the time constant of the meter. The principal results are outlined in the following paragraphs.

Signal-to-Noise Ratios. In visual perception, the criterion for the detectability of a signal involves, to a first approximation, the ratio of peak signal to mean noise background (without signal), whereas in aural or meter detection the important ratio is that of the signal energy in the particular harmonic component (the constant or d-c component in the aperiodic meter) to the noise energy in the frequency region surrounding this component, which the audio or meter filter passes without appreciable attenuation. The ear is known to have the power to discriminate frequency, a property which is equivalent to surrounding the signal by a filter of a certain critical bandwidth. The advantage of this natural filtering action of the ear is that it does not require knowledge of the prf.

When one listens to or looks for a signal with the help of one's receiving apparatus, it is done against a noise background, man-made or natural, which tends to obscure perception. The ability to detect a signal depends[585] on the magnitude of the ratio of the signal at the point of reception (i. e., on the screen, at the earphones, or on a meter) to the appropriate noise background.

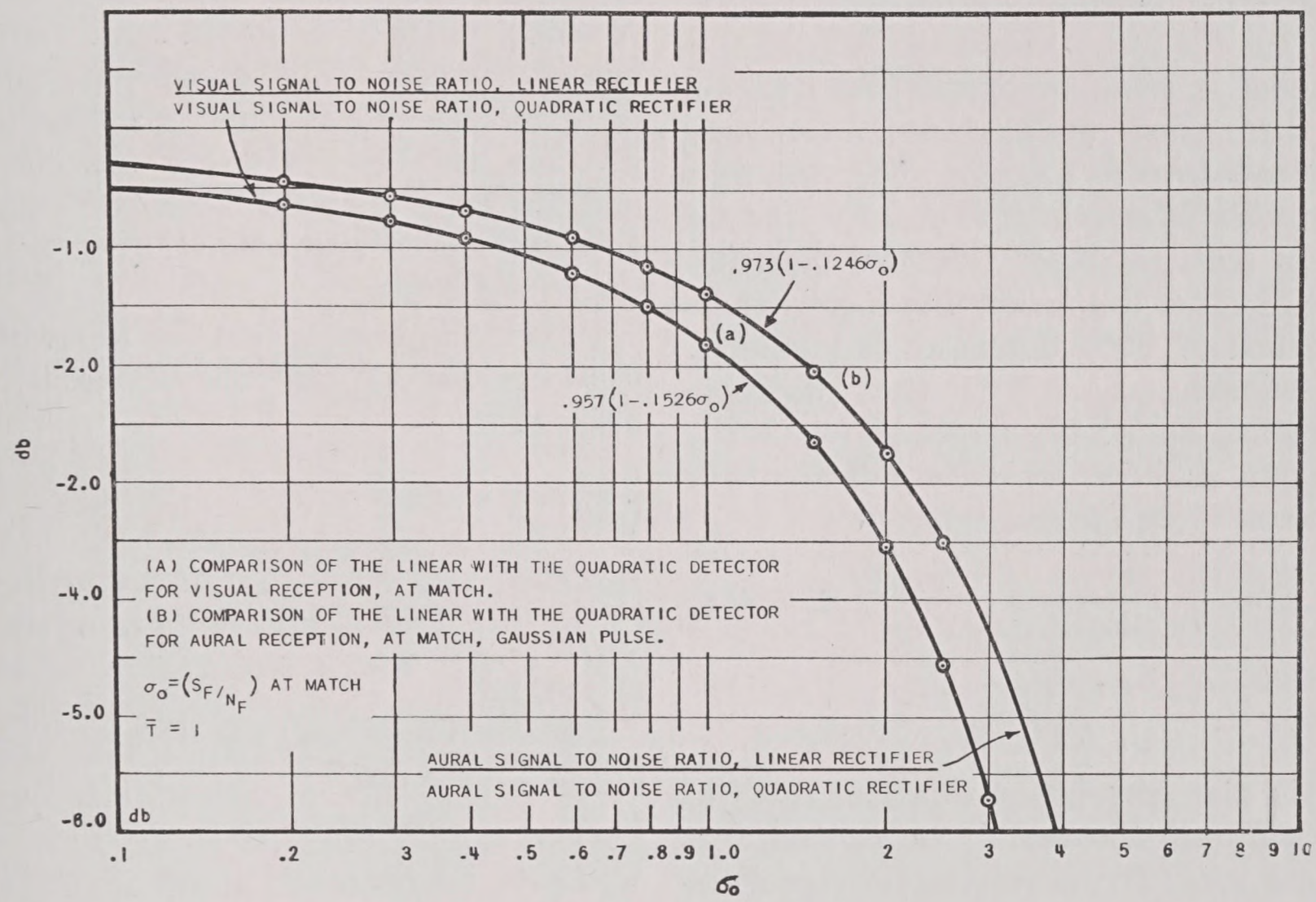


FIGURE 6. Comparison of the linear with the quadratic detector in aural and visual reception.

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For visual reception involving quadratic detection it was shown that

$$\left(\frac{s_V}{n_V}\right)_{\text{quad}} = \left(\frac{s_F}{n_F}\right)^2, \tag{53}$$

where (s_V/n_V) is the (peak) video signal-to-noise ratio perceived on the scope, and (s_F/n_F) is the ratio of the rms signal to noise, before rectification but after filtering by the i-f stages. For linear rectification equation (53) becomes

$$\left(\frac{s_V}{n_V}\right)_{\text{lin}} = \gamma_0\left[\left(\frac{s_F}{n_F}\right)^2 - 2\gamma\left(\frac{s_F}{n_F}\right)^{2K}\right], \tag{54}$$

$$\gamma_0 = \frac{1}{2}\left(\frac{4}{\pi} - 1\right)^{-\frac{1}{2}} = 0.957, \gamma = 0.0763, \kappa = 1.50.$$

When the signal is small in comparison with the rms noise, i.e., when $(s_F/n_F)^2 \ll 1$, *we may neglect the second term in equation* (54), *and then the linear rectifier behaves almost exactly like the quadratic.* In fact, for most practical purposes we may set $\gamma_0 = 1$, so that under these conditions the performance of both detectors is identical. For strong signals $(s_F/n_F \geqq 1)$ the quadratic detector becomes noticeably superior (> 2 db) to the linear one, as shown by curve *a* of Figure 6.

In aural work it was found that

$$\left(\frac{s_a}{n_a}\right)_{\text{quad}} = \frac{1}{T(\dot{\xi}_0 2\Delta f_e)^{\frac{1}{2}}}\int_{-\infty}^{\infty}\frac{s_F(t)^2}{{n_F}^2}\,dt, \tag{55}$$

with

$$\dot{\xi}_0 = \int_0^{\infty} r_0(t)^2\,dt,$$

where $r_0(t)$ is the correlation function of the input noise without the carrier or central frequency. Here s_a/n_a is the rms audio signal-to-noise ratio perceived in the earphone, and Δf_e is the width of a rectangular earphone filter response. The corresponding expression for the linear rectifier becomes

$$\left(\frac{s_a}{n_a}\right)_{\text{lin}} = \frac{\gamma_{0,0}}{T(2\Delta f_e)^{\frac{1}{2}}}\int_{-\infty}^{\infty}\left[\frac{s_F(t)^2}{{n_F}^2} - 2\gamma\left(\frac{s_F(t)}{{n_F}^{2K}}\right)\right]dt \tag{56}$$

where $\gamma_{0,0}$

$$= \left\{\sum_{n=0}^{\infty}\left[\frac{(2n)!}{2^{2n}\,n\,!\,(n+1)\,!}\right]^2\int_0^{\infty} r_0(t)^{2n+2}\,dt\right\}^{-\frac{1}{2}}.$$

Again, if the signal-to-noise ratio is small, the second term in equation (56) may be omitted. For practical purposes the difference in behavior of the two detectors is important only when the second term of equation (56) becomes significant (see Figure 6, curve *b*).

Quantitative Expressions. The optimum (or "matched") i-f filter is the conjugate of the Fourier transform of the pulse, not only for visual reception, as has been previously determined, but for aural or meter reception as well. The addition of a video filter to such an i-f design theoretically offers no improvement in visual reception under ideal conditions (which apparently are in general not quite realized experimentally). Then if σ_0 represents s_F/n_F at match, the results of the analysis[585] may be summarized quantitatively. For, knowing the values of the *physically* minimum detectable signal-to-noise ratios for the various types of presentations—A scope, ungated or gated aural reception, and use of a meter—it is possible to calculate and compare the relative and absolute sensitivities of these methods. The use of a gaussian pulse and filter was assumed, since the gaussian shape is a reasonable approximation to actual shapes used in practice.

Under this assumption the following relations were derived for the case of visual methods of indication.

$$\left(\frac{s_V}{n_V}\right)_{\text{quad}} = \sigma_0^2, \tag{57}$$

$$\left(\frac{s_V}{n_V}\right)_{\text{lin}} = 0.957\sigma_0^2\,(1 - 0.1526\sigma_0), \quad \sigma_0^2 \leqq 10,$$

at match.

For aural reception the necessary formulas for *ungated* noise are

$$\left(\frac{s_a}{n_a}\right)_{\text{quad}} = \frac{0.633\sigma_0^2}{T_0(\Delta f_e f_b)^{\frac{1}{2}}}, \tag{58}$$

$$\left(\frac{s_a}{n_a}\right)_{\text{lin}} = \frac{0.616\sigma_0^2}{T_0(\Delta f_e f_b)^{\frac{1}{2}}}(1 - 0.1246\sigma_0), \quad \sigma_0^2 \leqq 10,$$

where T_0 is the pulse period, at match, and f_b is a frequency relating the width of the pulse (or filter) to its duration; that is, the pulse is proportional to $e^{-\omega_b{}^2 t^2/2}$, $\omega_b = 2\pi f b$. Here Δf_e is the width of the critical ear or audio filter, whichever is the narrower. When the background is gated, equation (58) becomes

$$\left(\frac{s_a}{n_{aG}}\right)_{\text{quad}} = \frac{0.633\sigma_0^2}{(T_0\tau_G\Delta f_e f_b)^{\frac{1}{2}}}, \tag{59}$$

$$\left(\frac{s_a}{n_{aG}}\right)_{\text{lin}} = \frac{0.616\sigma_0^2}{(T\tau_G\Delta f_e f_b)^{\frac{1}{2}}}(1 - 0.1246\sigma_0), \quad \sigma_0^2 \leqq 10,$$

where now τ_G is the duration of the "on" or transmitting period of the gate.

The expression for the periodic meter (still for gaussian pulses) was shown to be

$$\frac{s_m}{n_m} = 1.156 \frac{\left[1 + \frac{1}{2}\left(\frac{\Delta f_m}{\Delta f_a}\right)^2\right]^{\frac{1}{4}}}{\left(\frac{\Delta f_m}{\Delta f_a}\right)^{\frac{1}{2}}} \cdot \left[\left(\frac{s_a}{n_{a(G)}}\right)^2 - 0.1526\left(\frac{s_a}{n_{a(G)}}\right)^3\right], \quad (60)$$

$$\left(\frac{s_a}{n_{a(G)}}\right)^2 \leqq 10,$$

at match, where the second detector of the receiver may be either linear or quadratic. In equation (60), s_m/n_m represents the ratio of the rms signal to the rms noise detected by the meter, and Δf_m and Δf_a are widths of rectangular meter and audio filters equivalent to the actual gaussian ones assumed. The equivalence is given analytically by $f_K = \Delta f_K/\pi^{\frac{1}{2}} = 0.565\Delta f_K$, where K is an arbitrary subscript. The quantity Δf_m appearing in equation (60) is twice the equivalent rectangular filter width of the meter.

Summary of Results. A comparison of absolute sensitivities of the various methods is shown in Table 4, constructed on the assumption that the pulse is gaussian and the filter is matched to it. The various constants are $f_b = 4 \cdot 10^5$ c, the width between half-power points is 2/3 mc, and the equivalent rectangular pulse is 7.1×10^5 c. Further, the total duration of the gate is $\tau_G = 5 \cdot 10^{-6}$ sec, and $T_0 = 10^{-3}$ sec (prf = 10^3 c). Two different audio filters are used: $\Delta f_e = 50$ or 5 c; and three different meter filters: $\Delta f_m = 2$, 0.2, or 0.1 c (actual width 1, 0.1, or 0.05 c), each with the same audio filter $\Delta f_e = 50$ or 5 c.

The aperiodic meter has the advantage of not requiring knowledge of the prf and has potentially great sensitivity if spurious fluctuations in gain can be balanced out. The periodic meter is less sensitive to gain fluctuations, but it is incorrect to assume that the signal-to-noise ratio is as favorable for a moderately narrow audio filter and a final very narrow meter filter as for a single audio filter having the same width as the latter. See, for example, Figure 7. *Meter methods can be made more sensitive than the A scope if long time constants are available, and this depends on tactical considerations. Gating is also necessary.*

Curves were drawn[h] to show the power required to achieve a given signal-to-noise ratio as a function of pulse length and i-f filter width, when the pulse and filter are not matched to each other (i.e., are not related as Fourier transforms). Figure 8 is included here as an example of these. Although the best i-f filter is the Fourier transform of the pulse, in aural reception the best pulse is not the Fourier transform of the filter (though it is in visual), for the problem of varying the filter with a fixed pulse is not the same as that of a fixed filter and varying pulse. *Instead, the best results in meter or audio detection are obtained by using long pulses.*

TABLE 4. Comparison of sensitivities of visual, aural, and meter methods of presentation.*

At match		Quadratic 2nd detector		Linear 2nd detector	
Physically minimum detectable signal		Δf_a 50 c.	Δf_e 5 c.	Δf_e 50 c.	Δf_e 5 c.
(Visual)	0.0 db (pessimistic)	$\sigma_0 =$ 0.0 db		+1.0 db	
(s_V/n_V)	−5.0	−2.5 db		−1.7 db	
	−10.0 (optimistic)	−5.0 db		−4.4 db	
(Aural)					
(s_a/n_a)	+10.0 (pess.)	+13.5	+8.5	>13.5	+11.2
no gate	0.0 (opt.)	+8.5	+3.5	>13.5	+4.8
(Aural)					
(s_a/n_{aG})	+10.0 (pess.)	+2.0	−3.0	+2.9	−2.5
gate	0.0 (opt.)	−3.0	−8.0	−2.5	−7.8

	Δf_m	Time constant $= 2/\Delta f_m$	$\sigma_0 = \left(\frac{s_F}{n_F}\right)_{\text{at match}}$ $\sigma \sim$ Power required for minimum detectable signal.			
Periodic metering	2 c.	1 sec	−6.7	−9.3	−6.3	−9.0
$(s_m/n_m) =$	1/5	10	−9.3	−12.0	−9.0	−11.5
0.0 db gated noise, lin., rect.	1/10	20	−10.0	−12.4	−9.8	−12.2
Aperiodic metering	2	1	−10.0		−9.7	
$(s_m/n_m) =$	1/5	10	−15.5		−15.2	
0.0 db	1/10	20	−16.5		−16.3	

*The equivalent rectangular pulse is 1.41 μsec long. $T_0 = 10^{-3}$ sec, $\tau_G = 5 \cdot 10^{-6}$ sec; $f_b = 4 \cdot 10^5$ c.

[h] Figures 7 to 11 of reference 585.

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The dependence of necessary signal power on the prf was studied, and found to be different in visual and aural detection. The variation with gating and audio filter width was also examined, and the results are illustrated by Figure 9. It was further established[585] that long pulses are more easily detected for given mean input power, whereas in visual detection the pulse length is immaterial (to a first approximation).

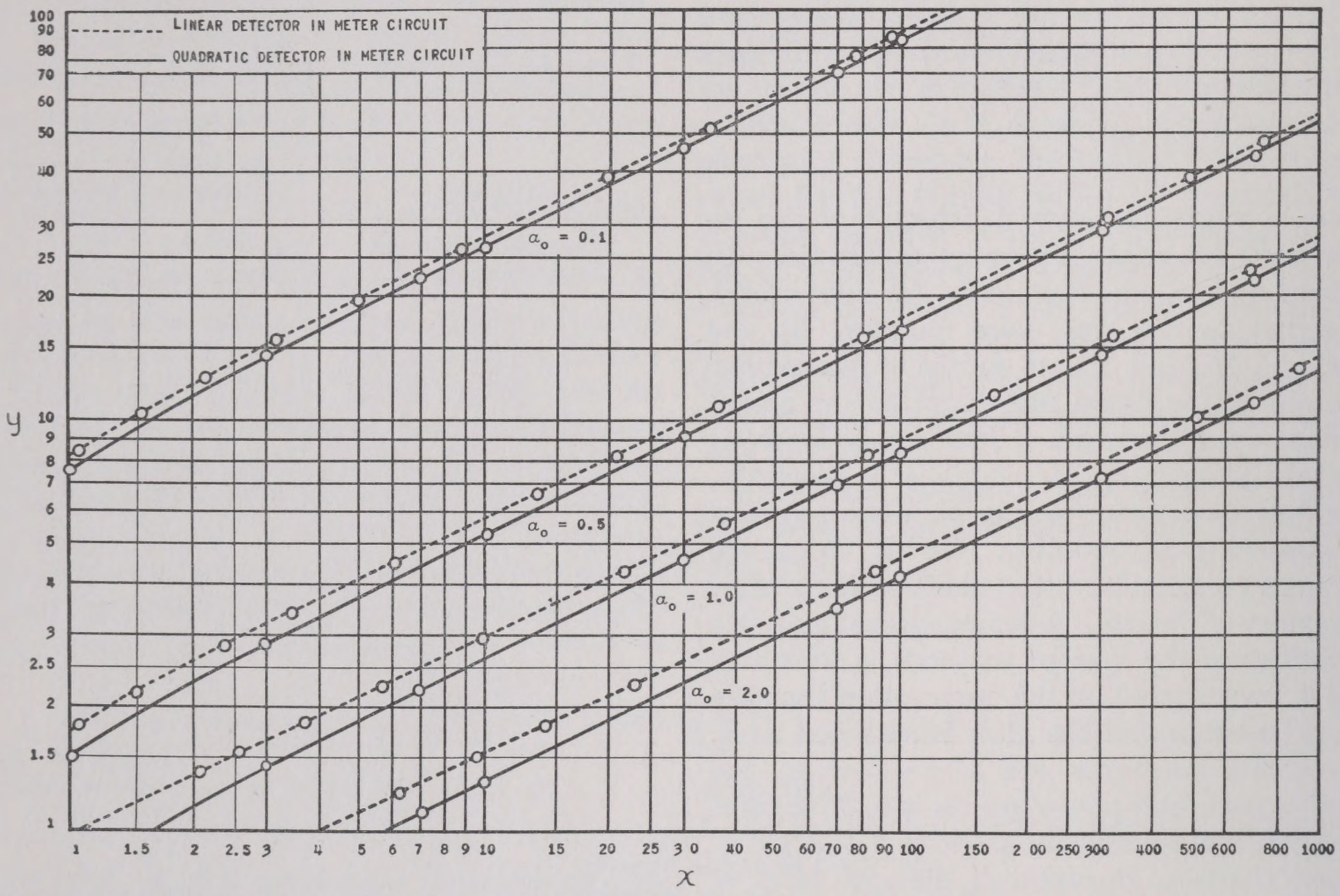


FIGURE 7. Width of the equivalent earphone filter Δf_e used in aural detection of the minimum detectable signal in the presence of noise as a function of the audio filter width Δf_a used in meter detection of the same signal-to-noise ratio a_o.

$$y = \frac{\Delta f_e}{\Delta f_m} = \frac{\text{Width of single audio filter, or filter used in aperiodic metering, } A = 1}{\text{Width of periodic meter filter}}$$

$$x = \frac{\Delta f_a}{\Delta f_m} = \frac{\text{Width of audio filter used with meter}}{\text{Width of periodic meter filter}}$$

$$a_o = \text{Minimum detectable signal-to-noise ratio in periodic metering scheme}$$

$$A = \frac{\text{Minimum detectable signal-to-noise ratio in periodic metering scheme}}{\text{Minimum detectable signal-to-noise ratio in "ear scope" or, when } A = 1, \text{ in aperiodic metering system}}$$

EFFECTS OF INTEGRATION ON SIGNAL VISIBILITY

The criterion established in the earlier work[585] for the signal-to-noise ratio, although on the whole quite adequate for the purposes described above, was found to be insufficiently refined when the detailed question of integration, by eye or by mechanical devices, arose. Accordingly a number of studies were begun on this problem, not only to provide theoretical guidance or confirmation of experimental work being carried out by the AJ investigators at the time, but to suggest, if possible, improved AJ techniques.

Early Qualitative Approach. One of the first problems investigated was the effect of integration on the visibility of weak signals through

[redacted]

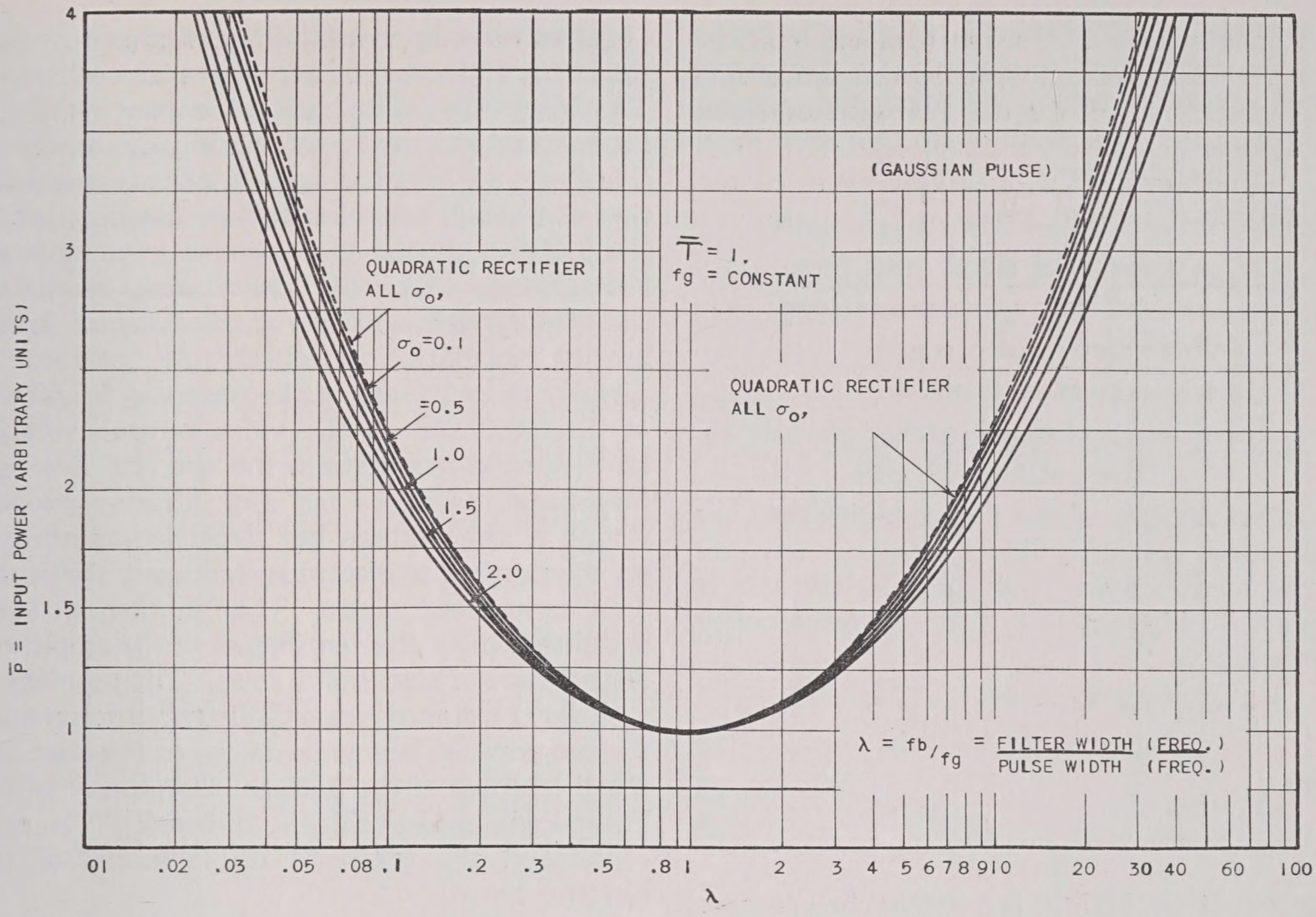


FIGURE 8. Input power to the intermediate frequency as a function of i-f filter width for aural reception of the minimum perceivable signal, gated or ungated noise.

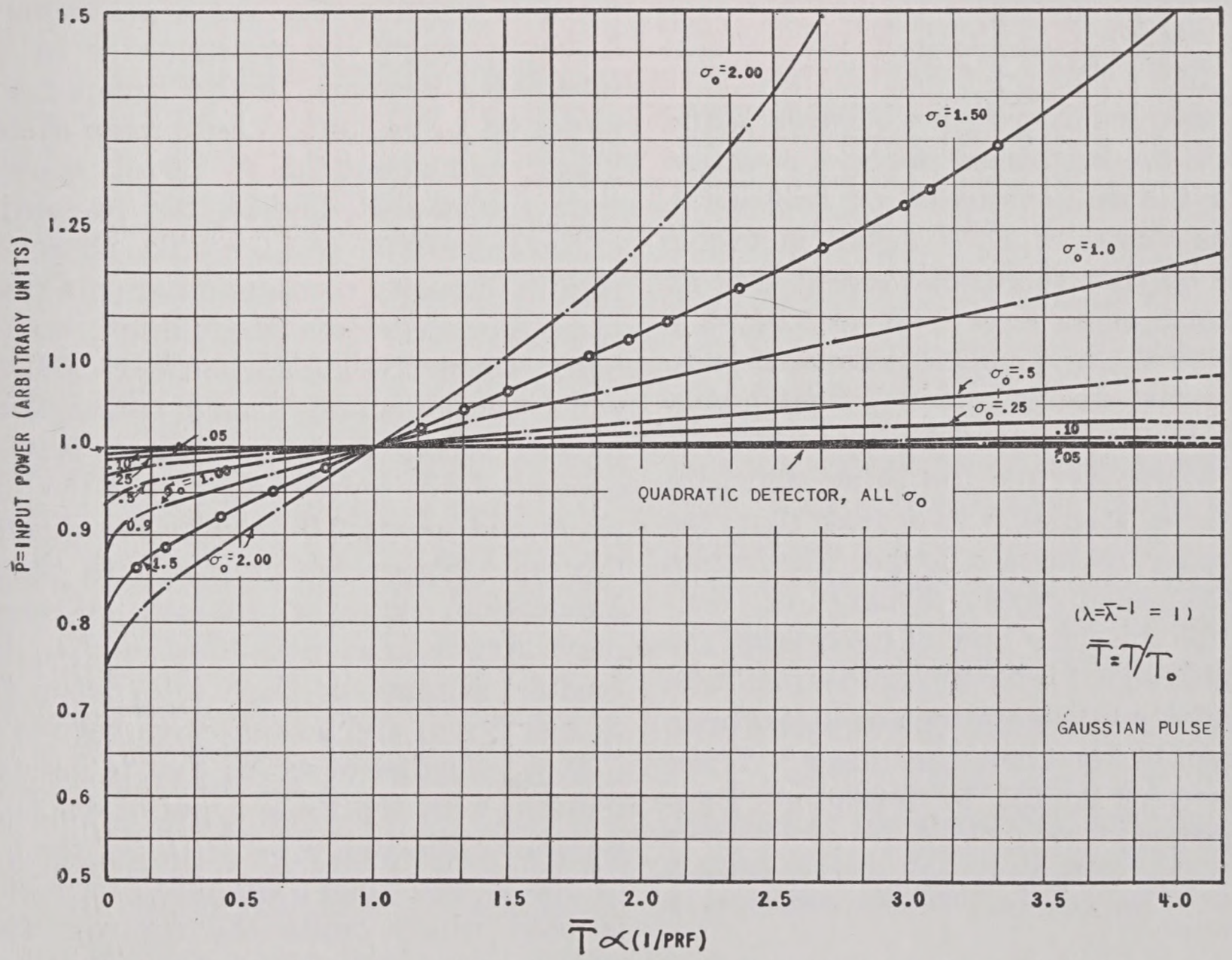


FIGURE 9. Input power to the intermediate frequency as a function of pulse period for aural reception, at match, with ungated noise.

noise on a standard A scope (deflection modulation).[575] The general form of the probability distribution[836, 837, 838] for the envelope of signal and noise is

$$P(\eta, \sigma)d\eta = 2\eta e^{-\eta^2 - \sigma^2} J_0(2i\sigma\eta)d\eta, \quad i^2 = -1, \qquad (61)$$

where

$$\eta = \frac{\text{Envelope of signal and noise}}{\text{Rms voltage of noise envelope}},$$

$$\sigma = \frac{\text{Voltage amplitude of signal}}{\text{Rms voltage of noise envelope}}$$

$$= \frac{\text{Rms voltage of signal (carrier removed)}}{\text{Rms voltage of noise}}.$$

The characteristic of the detector-plus-amplifier combination is usually linear or square law, and can be made square root; that is, the output ρ equals η^n, where $n = 1$, 2, or $\frac{1}{2}$, respectively. Then we have

$$P(\rho, \sigma)d\rho = P(\eta, \sigma)d\eta = P_0(\rho)e^{-\sigma^2} J_0(2i\sigma\rho^{1/n})d\rho, \qquad (62)$$

where

$$P_0(\rho) = \frac{2}{n} \rho^{\frac{2}{n} - 1} e^{-\rho^{\frac{2}{n}}}.$$

From equation (62) it is possible to compare, say, the linear and quadratic displays, by setting the "contrast"[i] ratios equal:

$$\frac{P(\rho_1,\sigma)}{P(\rho_1,0)} = \frac{P(\rho_2,\sigma)}{P(\rho_2,0)}, \qquad (63)$$

in order to determine the relation between ρ_1 and ρ_2 which makes the brightness ratios of equation (63) equal for the same value of σ. In general, the conditions under which a signal is visible through noise on the oscilloscope screen are: an average contrast of at least 1.02 to 1.04 at a deflection where there is sufficient brightness to make the contrast visible and sufficient homogeneity to allow the eye (and brain) to average accurately. Moreover, for the same signal-to-noise ratio these studies[575] indicated that the quadratic display requires a longer integration time than the usual linear display—or, conversely, that for the same time of integration the minimum visible signal is larger for the quadratic display. Similarly, a square-root or logarithmic display seemed better than the linear. These investigations were limited to deflection-modulated presentations.

[i]When $P(\rho,\sigma)/P(\rho,0) < 1$, then its reciprocal is termed the contrast.

Quantitative Approach. It was found, however, that the above approach was still too naive. The integration time did not appear explicitly in the analysis, as it should in any theory of this type, nor was the case of intensity modulation examined. A more refined examination of the problem showed that what the eye averages is *brightness*, a quantity also directly related to the display characteristic of the system. In intensity modulation the observable "pattern" is directly proportional to the observed brightness or intensity and to the video output voltage. In deflection modulation, the eye still averages brightness, which is *not* now directly proportional to the voltage but depends (as always) on the number of electrons striking a particular area under observation. This number, in turn, is influenced by the *distribution* of the amplitude of the wave of signal plus noise. The problem in the former instance is essentially two-dimensional, the range sweep being one degree of freedom and the brightness of the pattern, the other. In the latter case an additional "dimension" is used —namely, the (vertical) displacement of the electron beam.

The problem was found to be less tractable than it first appeared, and was finally laid aside for more urgent work. A few preliminary results, however, might be mentioned. In intensity-modulated systems, firstly, square-law systems appeared to be 1.0 to 1.5 db more effective than linear, and about 2.5 to 3.0 db more effective than square-root devices, for integration times of the order of 0.5 to 5 sec. The effects of saturation in intensity modulation are always deleterious. For deflection modulation, on the other hand, when the integration device is a camera which considers only a small rectangle of screen, it was found that square-root systems yield about 1.5-db improvement over the linear displays and about 2.0-db over the quadratic, for the same integration times. With photographic integration, however, intensity-modulated displays appear to be more effective than deflection-modulated ones for short integration times (up to 4 or 5 sec) and less effective beyond that.

It was further observed that in intensity modulation, with the three types of display characteristic considered ($n = \frac{1}{2}$, 1, 2), the best value of bias is zero when a simplified form of criterion is used which omits the contrast term $\epsilon\bar{b}(0)$

($\bar{b}(0) \equiv$ the mean brightness without signal). When the contrast constant ϵ is different from zero (0.04 is a reasonable value), there exists a nonvanishing optimum bias, which increases with longer integration times.

The analysis of deflection modulation where the integrating device is a camera was carried out for two special cases: (1) a small area element of the scope screen, and (2) a narrow vertical strip of screen, of moderate height Δr. It was shown that an optimum value of Δr exists. The complete theory demands, however, that the area effectively viewed by the eye (or camera) also have a reasonably large width Δu, with the result that correlation between the traces entering and leaving the area must be considered. It was at this point that analytical difficulties and other more pressing problems forced abandonment of the work.

Detailed experiments, however, were carried out throughout World War II at the Radiation Laboratory of the Massachusetts Institute of Technology on problems of this general nature, and theoretical studies similar in nature to the above were also made there.

6.2.3 Other Applications of Noise Studies

While much of the work was concerned with the analysis of spectra and the study of the jamming properties of noise against pulsed signals, some efforts were made to determine analytically the spectral nature of the output of some of the noise sources used in jammers and to apply the results of the fundamental studies to other problems which arose.

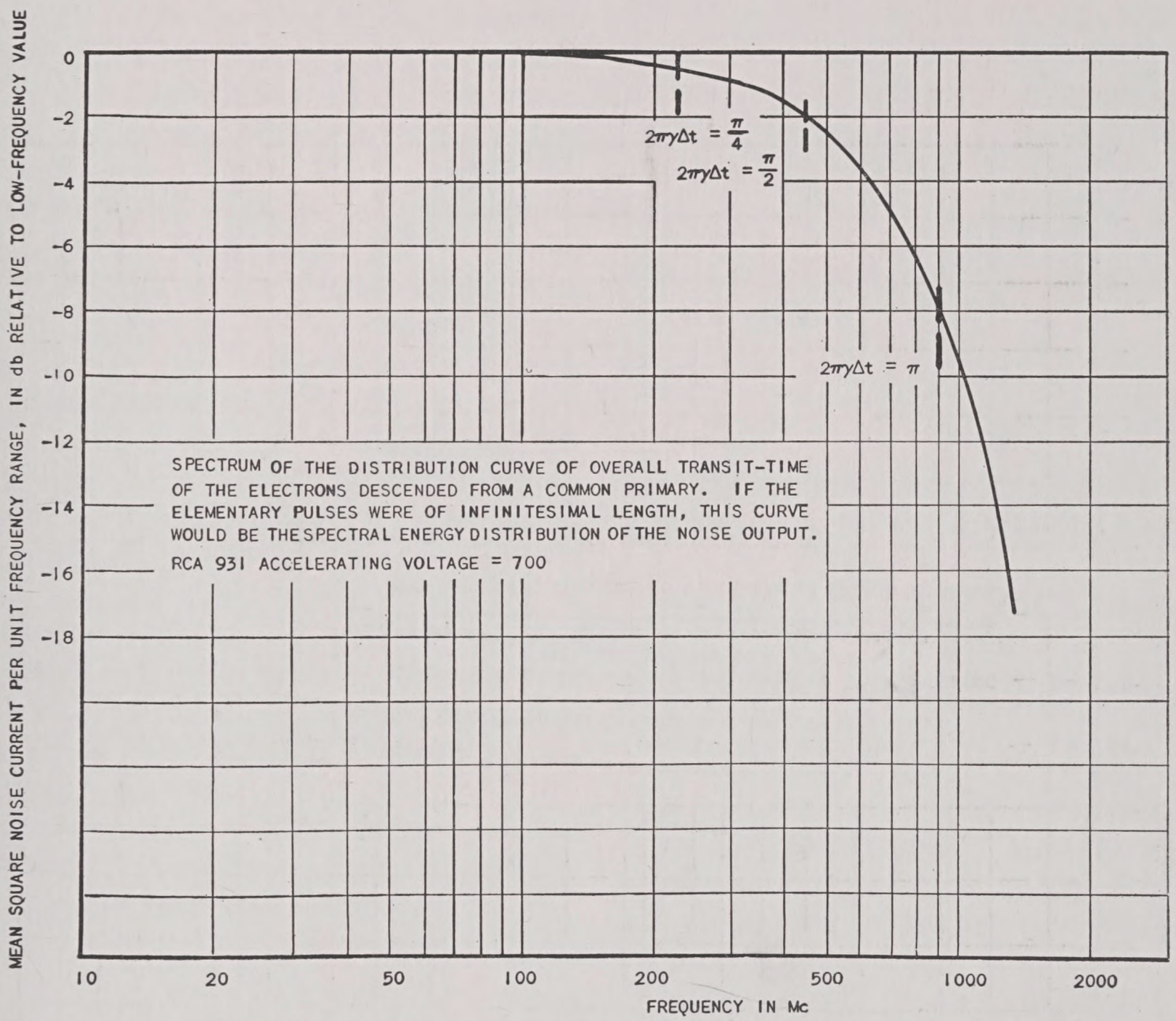


FIGURE 10. Spectrum of the distribution curve of overall transit time of the electrons descended from a common primary.

NOISE OUTPUT OF PHOTOMULTIPLIERS

Among the earliest of such studies was a calculation of the frequency spectrum of the noise output of the RCA 931 photomultiplier tube.[522] It was discovered that this tube might provide

a suitable direct source of noise in the frequency band of the enemy's radar and communications equipment. Accordingly, a theoretical estimate of the frequency dependence of the noise output from this tube was undertaken.

On the assumption of high vacuum and negligible space charge, it was found that the noise output falls off as the frequency increases, because of (1) the finite velocities of the electrons

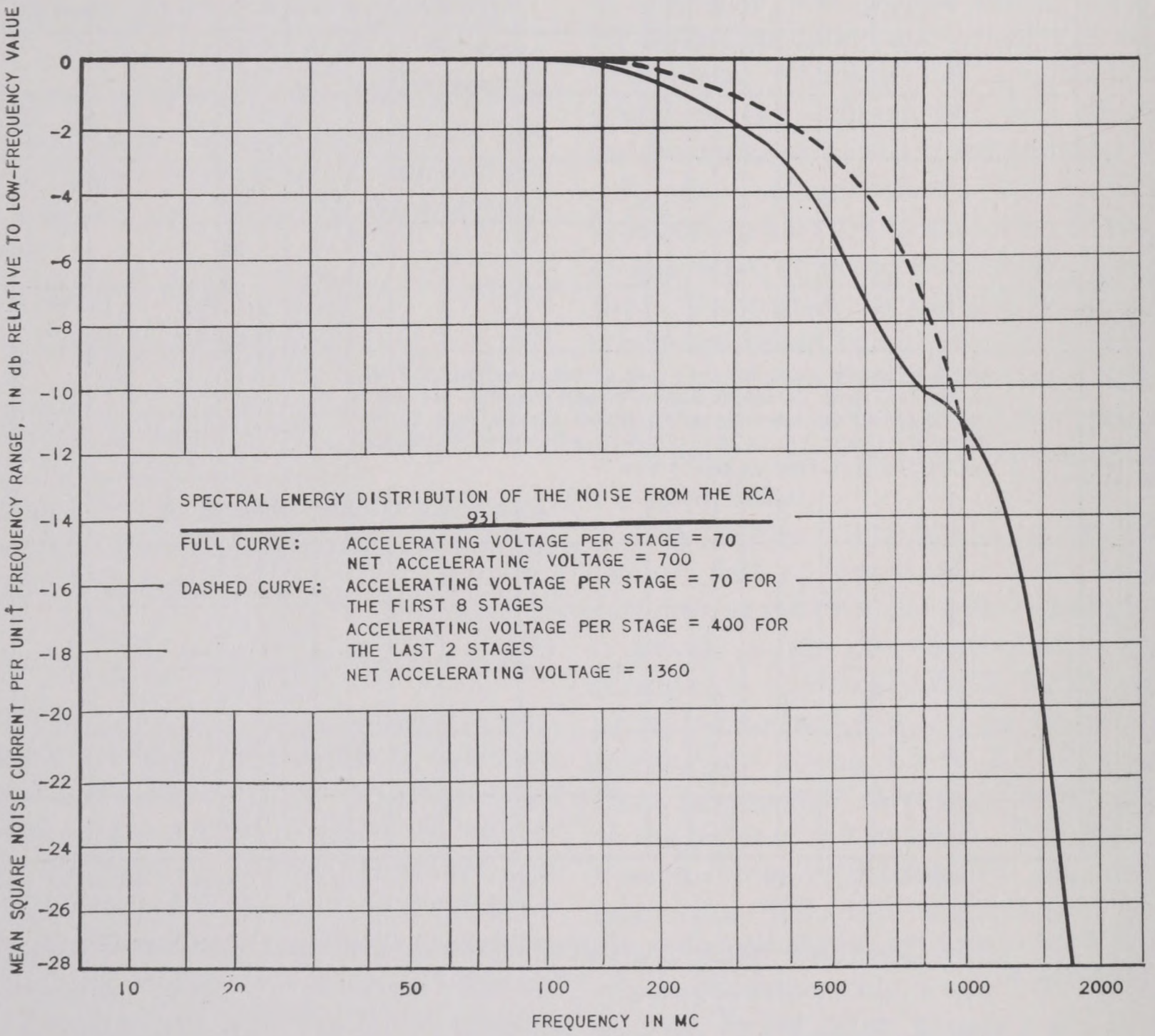


FIGURE 11. Calculated spectral energy distribution of the noise from the RCA 931 tube.

drop 6 db around 500 mc. These frequencies may be increased by raising the accelerating voltage, the increase being somewhat more than proportional to the square root of the voltage. Another method of extending the spectrum is to increase only the last two interstage voltages, the preceding ones being left unchanged. Raising each of the last two to 400 v results in the spectrum being down only 4 db at 600 mc. Some

as they approach the anode and (2) the spread in time of arrival at the anode, of the electrons descended from the same primary. The spectrum is flat at low frequencies but approaches zero as the frequency is increased; this result is evident from Figures 10 and 11. When the tube is operated with 70 v per stage, the output should be down about 1 db around 200 mc but should

increase in the preceding interstage voltages, however, may be necessary to prevent excessive distortion of the electron orbits. Then, with a net accelerating voltage of about 1,500, and the interstage potentials increased to 400 in the last two stages, the 931 might be an adequate noise source in the 550- to 600-mc range. (Because of approximations in the calculations, and varia-

tions in the dimensions of individual tubes, the numerical results above may not be more accurate than ±3 db.)

Noise Output from Gas Tubes in Magnetic Fields

Experimental work on noise sources (see Chapter 2) indicated that an excellent source of high-level, wide-band noise could be obtained from a low-pressure gas-discharge tube when a magnetic field of suitable strength was applied. A theoretical study[j] was undertaken in an attempt to explain and predict the nature of the spectral output of such tubes.

It is well known that in the so-called plasma—a region in a gas discharge where the number of positive ions is equal to the number of negative ions of equal charge and the ion density is uniform—free oscillations of the ions may occur with well-defined frequencies. These frequencies depend on the ion mass, the ion charge, and the ion density, and on nothing else, provided thermal motion is neglected. It is easily shown that for ions of a given charge sign, the frequency is given by $(e\rho/\pi M)^{\frac{1}{2}}$, when e = ion charge, M = ion mass, and ρ = charge per unit volume due to ions of one sign (or the other). That is, *high ion densities give rise to high oscillation frequencies*, an observation on which the qualitative results of the analysis are based.

Results of the Analysis. If an electron current per unit area I_0 leaves the cathode, the rate of ion production per unit volume is

$$S(x) = 2\left(\frac{I_0}{e}\right)\left(\frac{1}{l}\right)\left(\frac{a_0}{x}\right)^{\frac{1}{2}}, \tag{64}$$

where l is the electron mean free path of ionization and x denotes the position between cathode and anode; the quantity a_0 is $(2V_0mc^2/eH^2)^{\frac{1}{2}}$, where V_0 is the potential at a flat portion of the orbit, m is the electron mass, c the velocity of light, e the charge on the electron, and H is the magnetic field strength (in gaussian units). The distribution function $f = f(x, v)$ is defined as the number of ions per unit volume at position x, per unit velocity range at velocity v. In other words, $f(x, v)dxdv$ is the number of ions (per unit cross-sectional area) between the planes x and $(x + dx)$ having velocities between v and $(v + dv)$. The function f assumes finally the form

$$f = \phi\, D(v), \tag{65}$$

where D is defined as $D(v < 0) = 0, D(v > 0) = 1$, and equation (65) is the representation sought. Furthermore, the quantity $\phi = \phi(W)$, with $W = \frac{1}{2}Mv^2 + eV$, is a function solely of the total energy of an ion at x having velocity v. The form of the functional relationship between ϕ and W is determined through the initial condition $(v = 0)$; namely,

$$\phi(eV) = \frac{-S(x)}{\frac{e}{m}\cdot\frac{dV}{dx}}. \tag{66}$$

The relation governing the potential distribution $V(x)$ is given by

$$\frac{d^2V}{dx^2} = -2\pi\,(2eM)^{1/2}\int_0^x \frac{S(x_0)dx_0}{\sqrt{V(x_0) - V(x)}}. \tag{67}$$

For the special case of equation (64), which applies to the present problem, it is found that

$$V = -12.4\left(\frac{I_0}{el}\right)^{2/3}(ea_0\,M)^{1/2}\,x^{5/3} = -Ax^{5/3}, \tag{68}$$

and for $\phi(W)$ when $v \pm 0$, we have

$$\phi(W) = \frac{6}{5}\,\frac{I_0Ma_0^{1/2}}{e^2lA}\left(x^{5/3} - \frac{M}{2eA}\,v^2\right)^{-7/10}. \tag{69}$$

In the calculations it is assumed that only a small portion of the mean free path of ionization of the electrons is spent within the ionizing region. Under actual conditions of operation this assumption is well justified. The further assumption that the potential drop within the ion-forming layer is negligible compared with the ionizing potential is also justified. It is, moreover, interesting to know what magnetic field strengths are required to turn the electron paths back toward the cathode before the free path of ionization is totally spent. In other words, how large must H be in order that infinite ion densities result? To an order-of-magnitude approximation, the critical value of $H = (H_c)$ is that for which a_0 just equals l; H_c is then about 140 gauss, the field strength for which h-f response of noise exists. The more complete analysis[730] showed that for tubes of the general specifications of the 6D4, for example,

[j] Part III of reference 730.

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appreciable oscillations at frequencies around 250 mc could be expected.

Effect of Clipping on Noise Spectra of Gas Tubes

It was found that clipping or distorting the waveform of the noise output of one of the above tubes, preferably the 6D4 (as its spectral level is considerably higher than that of the RCA 931), resulted in spreading of the spectrum.[589] Since broad spectra are needed in jamming, as is discussed elsewhere (see Section 6.2.1), an analytical study was undertaken to determine numerically the effects of limiting when the incoming wave consisted of random noise from a 6D4, 884, 178A, or 2D21 gas-tube noise source. The nonlinear devices examined were linear and quadratic rectifiers, with various cutoff and saturation voltages. The mathematical results are summarized in Section 6.2.1, equations (21) and (44). The qualitative results[589] for the 6D4 spectrum are outlined below.

Results for the 6D4 Tube. Clipping, whether at the "top" or "bottom" of the wave or both, always spreads the spectrum. For saturated nonlinear devices (or rectifiers, as they are often called), this spread is greatest when the ratio $b_0/\psi^{\frac{1}{2}}$ of cutoff voltage (measured from the operating point) to rms input noise voltage lies between 1.0 and 2.0 or between -1.0 and -2.0. For larger ratios the level of the output spectrum may be prohibitively low. It is further observed that clipping without saturation yields even greater spreads, and at higher levels, than do overloaded rectifiers operating under conditions otherwise the same, except for the parts of the spectra well away from the maximum. There is not a great difference between saturated linear and quadratic detectors so far as an increase in the width of the output spectrum is concerned. However, in many situations a linear dynamic response may be preferred for its generally higher output spectral levels, other factors being the same.

For optimum spread it is desirable to clip as heavily on the bottom as possible (i.e., $b_0/\psi^{\frac{1}{2}} \geqq 1.0$), but within the limits of available gain. It is also desirable to operate with little or no overloading, if practicable. Symmetrical clipping, where the operating point lies midway between cutoff and saturation, is unsatisfactory from the above point of view, as it does not yield sufficiently wide, high-level spectra. Extreme clipping, with $(b_0/\psi^{\frac{1}{2}} > 1.0)$, gives a good spread, but at prohibitively low levels. As noted before (see end of Section 6.2.1), the power in the d-c and continuous portions of the output are independent of the spectral shape. As clipping becomes more severe, a greater percentage of the output power is concentrated in the continuous spectrum, although the absolute level drops rapidly as $b_0/\psi^{\frac{1}{2}}$ is made more positive—that is, as the bias is made more negative. Figures 12 to 16 illustrate the general nature of the results.

Noise Transformers

Not only was the general analytical technique for the treatment of noise applied to specific problems involving jamming spectra or the output characteristics of noise sources, but also to other important questions involving noise. Among the latter was the problem of noise in transformer cores (see also Section 2.6). An approximate theory was accordingly developed for the eddy-current loss in transformer cores excited by h-f sine waves and by broad-band (video) random noise.[761] Some of the salient features of the analysis are outlined below.

Mathematical Analysis. First the boundary conditions were established, subject to which the field equations governing the distribution of the electric and magnetic fields in thin rectangular laminae must be solved. Then the skin depth δ_0 and the mean eddy-current loss $\overline{W}$ were determined for current- and voltage-fed transformers. The skin depth was defined here as the depth measured from the surface at which the eddy-current losses, due to the induced currents, are a fraction C $(C < 1)$ of their total value.

For sinusoidal excitation, analytically a special case of the noise problem, the skin depth is specified by the relation:

$$1 - C = \frac{\sinh \lambda_0 (1 - \delta_0/a) - \sin \lambda_0 (1 - \delta_0/a)}{\sinh \lambda_0 - \sin \lambda_0}, \qquad 0 < C < 1, \quad (70)$$

where $\lambda_0 = (2\omega_0 \mu_e \sigma a^2)^{\frac{1}{2}}$, with μ_e an effective permeability, σ the conductivity, $\omega_0 = 2\pi f_0 =$ the angular frequency of the exciting field, and $2a$ the lamination thickness; here C is taken to

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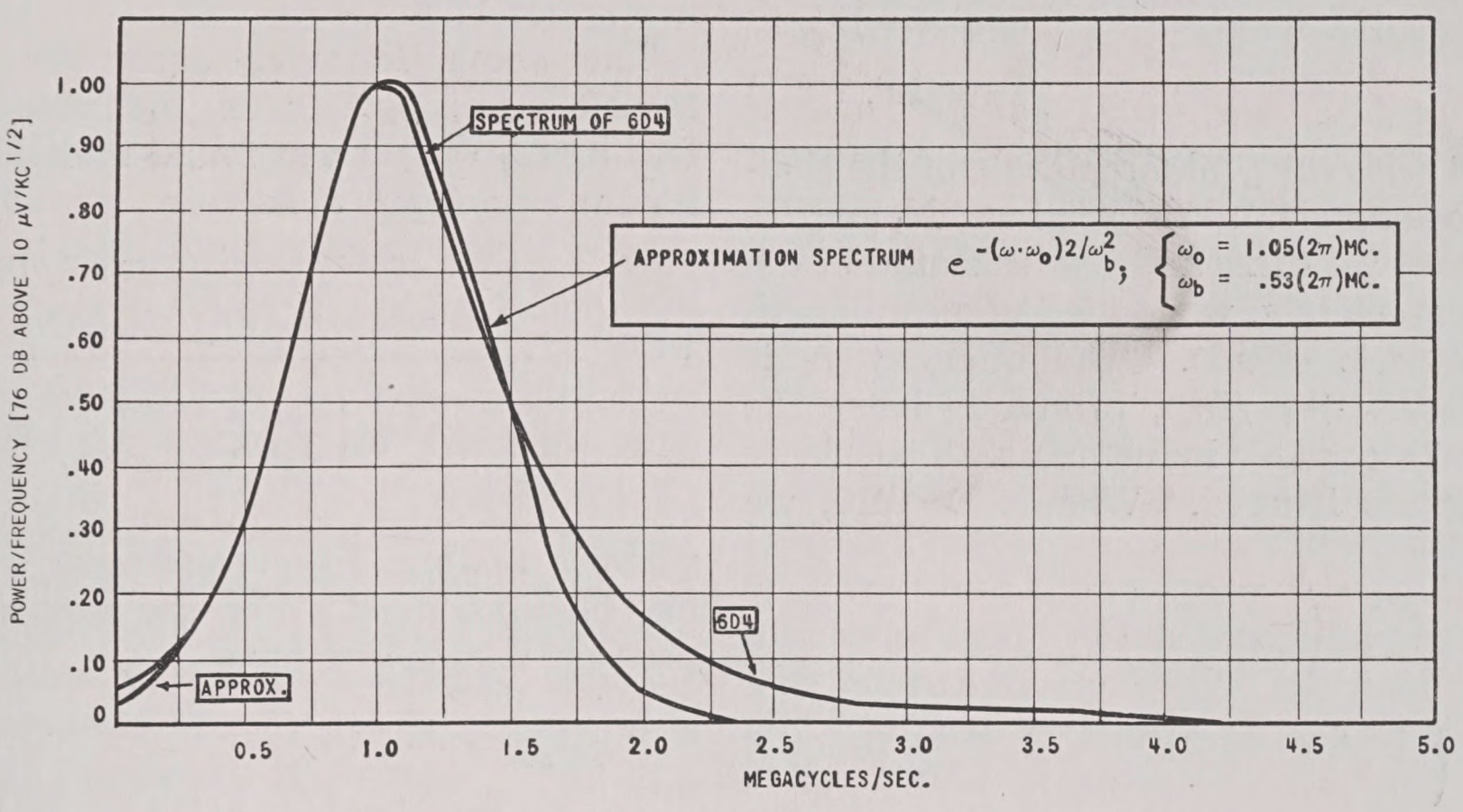


FIGURE 12. Spectrum of the 6D4 with approximation spectrum.

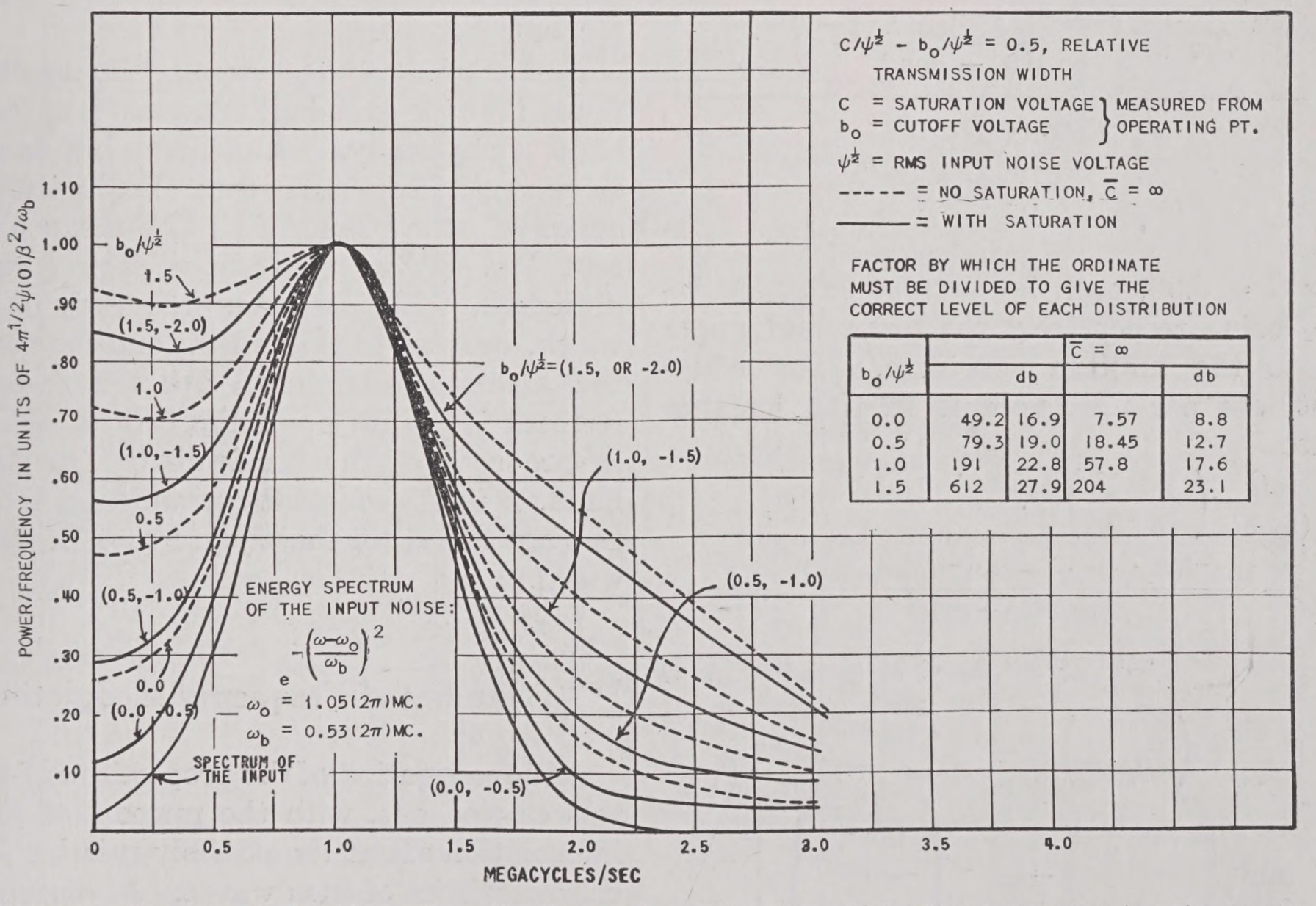


FIGURE 13. Spectra of the 6D4 after clipping and rectification of the input (random) noise by biased and saturated linear rectifier.

[redacted]

be 0.90. The mean eddy-current loss (per unit volume) is, when $\lambda_0 \leqq 0.10$,

$$\overline{W}_{\mathrm{I}} = \frac{a^2\sigma}{(\beta_0 a\sigma)^2}\left(\frac{N_1 V_{01}}{\sqrt{2}\,R_{01} l}\right)^2 \frac{1}{3}\,\frac{(\beta_0 a\mu_e\sigma\omega_0)^2}{1+(\beta_0 a\mu_e\sigma\omega_0)^2}, \qquad \frac{\beta_0}{a} \geqq 10^2, \quad (71)$$

where now V_{01} is the peak amplitude of the sinusoidal voltage applied to the primary, N_1 and R_{01} are the number of turns and the resistance of the primary, respectively, while l is the mean length of the magnetic circuit. The quantity β_0 is $(a\mu_e\sigma)^{-1}$ $(L_1/R_{01} + L_2/R_{02})$, L_1 and L_2 being the primary and secondary inductances. The effects of capacity are ignored. When $\lambda_0 > 0.10$, we may write

$$\overline{W}_{\mathrm{II}} = \frac{a^2\sigma}{(\beta_0 a\sigma)^2}\left(\frac{N_1 V_{01}}{\sqrt{2}\,R_{01} l}\right)^2 \cdot \left(\frac{1}{\lambda_0}\cdot\frac{\sinh\lambda_0 - \sin\lambda_0}{\sinh\lambda_0 - \cos\lambda_0}\right), \quad \frac{\beta_0}{a} \geqq 10^2. \quad (72)$$

The condition $\beta_0/a \geqq 10^2$ is a usual one in practice. For a uniform band of noise applied as a voltage to this primary, these results (70) to (72) are modified to

$$0.10 = \frac{\displaystyle\int_{\lambda_1}^{\lambda_2} \frac{\sinh\lambda\,(1-\delta_0/a) - \sin\lambda\,(1-\delta_0/a)}{\cosh\lambda - \cos\lambda}\,d\lambda}{\displaystyle\int_{\lambda_1}^{\lambda_2} \frac{\sinh\lambda - \sin\lambda}{\cosh\lambda - \cos\lambda}\,d\lambda}, \qquad \frac{\beta_0}{a} \geqq 10^2, \quad (73)$$

where $C = 0.90$, and $\lambda_{1,2} = (2\mu_e\ \sigma a^2\omega_{1,2}\ )^2$, ω_1 and ω_2 being respectively the lower and upper limits to the uniform spectrum. The eddy-current loss per unit volume in this instance becomes

$$\overline{W}_{\mathrm{I}} = \frac{a^2\sigma}{(\beta_0 a\sigma)^2}\left(\frac{N_1^2\overline{V_{01}^{\,2}}}{R_{01}^2 l^2}\right)\frac{1}{3}\cdot\left[1-\frac{\tan^{-1}(\beta_0 a\mu_e\sigma\omega_2) - \tan^{-1}(\beta_0 a\mu_e\sigma\omega_1)}{\beta_0 a\mu_e\sigma(\omega_2-\omega_1)}\right], \qquad \frac{\beta_0}{a} \geqq 10^2,\ \lambda_1 < \lambda_2 \leqq 0.10, \quad (74)$$

$$\overline{W}_{\mathrm{II}} = \frac{a^2\sigma}{(\beta_0 a\sigma)^2}\left(\frac{N_1^2 V_{01}^{\,2}}{R_{01}^2 l^2}\right)\frac{4}{\lambda_2^2\lambda_1^2}\left[\tan^{-1}\left(\frac{\tan\frac{\lambda_2}{2}}{\tanh\frac{\lambda_2}{2}}\right) - \tan^{-1}\left(\frac{\tan\frac{\lambda_1}{2}}{\tanh\frac{\lambda_1}{2}}\right)\right], \qquad \frac{\beta_0}{a} \geqq 10^2,\ \lambda_2 > \lambda_1 \geqq 0.10, \quad (75)$$

where now $\overline{V_{01}^2}$ is the mean-square noise voltage applied to the primary. Curves illustrating equations (71), (72), (74), and (75) are shown in Figures 17 and 18.

The above formulas apply for voltage-fed transformers, $\beta_0 > 0$; in the case of current feeding ($\beta_0 = 0$) it was found that the expansion for the skin depth δ_0 became

$$1 - C = \frac{\displaystyle\int_{\lambda_1}^{\lambda_2} \lambda^2\,\frac{\sinh\lambda(1-\delta_0/a) - \sin\lambda(1-\delta_0/a)}{\cosh\lambda + \cos\lambda}\,d\lambda}{\displaystyle\int_{\lambda_1}^{\lambda_2} \lambda^2\left(\frac{\sinh\lambda - \sin\lambda}{\cosh\lambda + \cos\lambda}\right)d\lambda}, \qquad 0 < C < 1 \quad (76)$$

where a uniform mean-square *current* spectrum has been assumed. For the eddy-current loss per unit volume, we have

$$\overline{W} = \frac{1}{2a^2\sigma l^2}\,(N_1^2\overline{I_1^2} + N_2^2\overline{I_2^2})\cdot\left[\frac{1}{2\pi\mu_e\sigma a^2(f_2-f_1)}\int_{\lambda_1}^{\lambda_2}\lambda^2\frac{\sinh\lambda - \sin\lambda}{\cosh\lambda + \cos\lambda}\,d\lambda\right], \quad (77)$$

where now $\overline{I_1^2}$ and $\overline{I_2^2}$ (the latter often zero) are the mean square applied primary and secondary currents, respectively, and N_2 is the number of secondary turns.

Results of Analysis. Among the results it was found that the skin depth decreases, as one would expect physically, with increasing lamination thickness, frequency, core conductivity, and effective permeability μ_e. The mean eddy-current loss in the constant-voltage transformer diminishes with increasing frequency or spectral width, because of skin effect, and increases with the thickness of laminae. For voltage-fed transformers $\overline{W}$ varies approximately as the inverse square root of the bandwidth. On the other hand, $\overline{W}$ in the constant-current cases is observed to vary about as the square root of the bandwidth.[761]

6.2.4 Studies of Frequency Modulation

An investigation of the properties of f-m waves was carried out, with the purpose of providing information about the possibly suitable jamming characteristics of such waves. As discussed elsewhere (Section 6.2.1), frequency modulation by noise was early considered a promising line of investigation. Then, too, frequency modulation

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by periodic waves, such as the sinusoid, or square, or triangular waves, offered possibilities for the jamming of communications, if not directly as a radar countermeasure.

Study of Types of Frequency Modulation

With communications jamming chiefly in mind, a study of four types of frequency modulation was begun.[552] The analysis considered (1) sinusoidal frequency modulation, (2) unsymmetrical sawtooth frequency modulation, (3) symmetrical sawtooth or "triangular" frequency modulation, and finally (4) frequency modulation by a square wave.

Sinusoidal Frequency Modulation. For (1), it was found that the modulated wave $E(t)$ is

$$E(t) = \hat{E}_c \left\{ J_0\left(\frac{\Delta\omega}{\omega_0}\right)\cos\omega_c t + \sum_{n=1}^{\infty}(-1)^n J_n\left(\frac{\Delta\omega}{\omega_0}\right)[\cos(\omega_c - n\omega_0)t + (-1)^n\cos(\omega_c + n\omega_0)t] \right\}, \qquad (78)$$

when $\hat{E}_c$ is the peak voltage of the (unmodulated) carrier, $\omega_c = 2\pi f_c$ is the carrier angular frequency, and $\Delta\omega$ is the (angular) frequency deviation from the carrier; $f_0 = \omega_0/2\pi$ is the rate at which this deviation is made, and J_n are the familiar Bessel functions of the nth order, first kind. Here the ratio $\Delta\omega/\omega_0 = \Delta F/f_0$ is termed the modulation index and denoted by b—see the relation following equation (2). The mean-square amplitude of the nth component is $A_n^2 = J_n^2(b)$. The number of significant sidebands is roughly $2b + 1$. One characteristic of the spectrum is that it tends to peak at $\pm nf \backsim \pm b$, i.e., at the limits of the band.

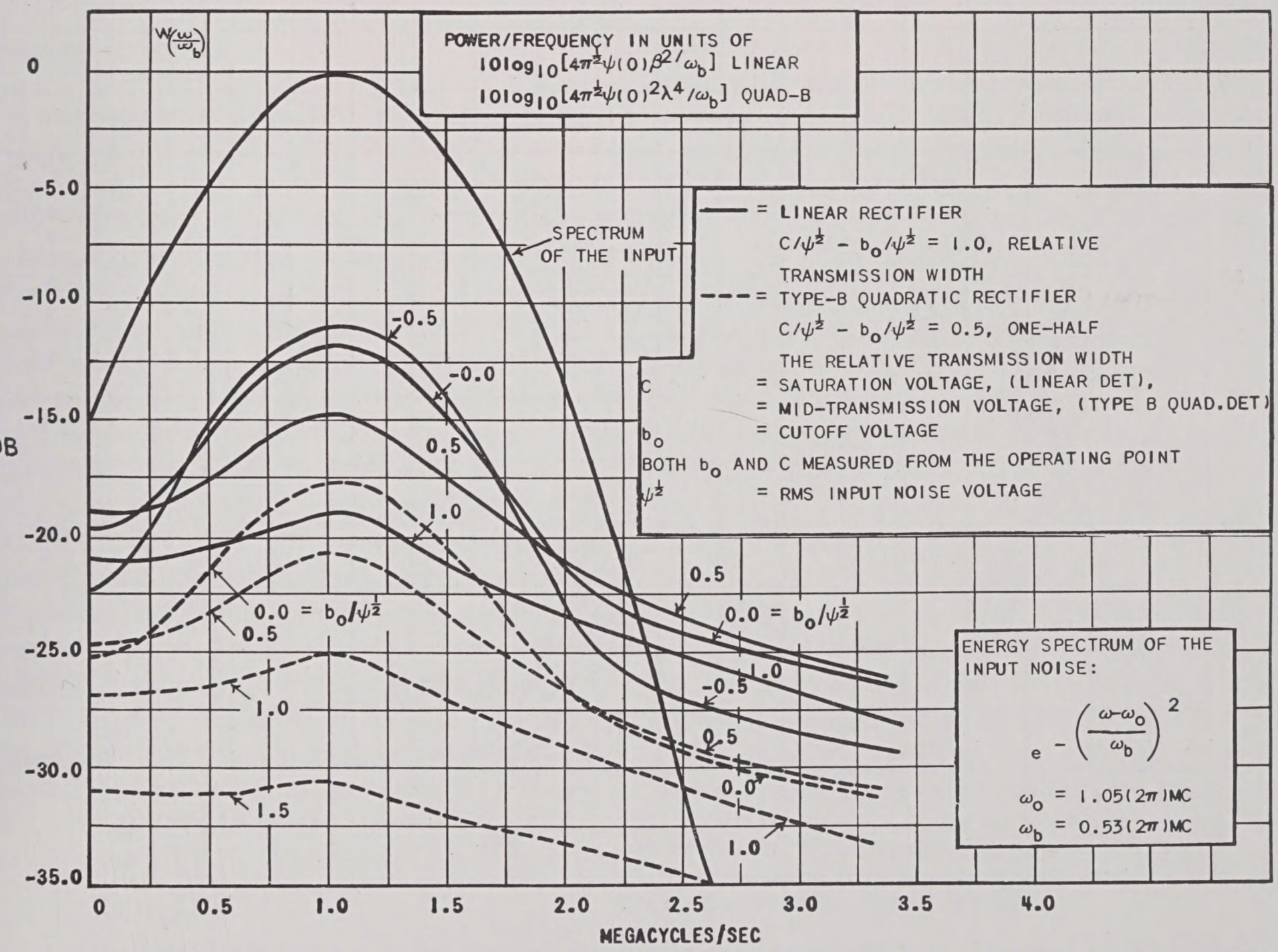


FIGURE 14. Relative spectral levels after rectification of the 6D4 output by linear and Type B quadratic rectifier (see Figure 5).

Sawtooth Frequency Modulation. In frequency modulation by a sawtooth wave (2), the output wave $E(t)$ may be resolved into an infinite number of components, on either side of the carrier f_c, spectrally speaking. The square of the modulus of the nth component has the form

$$\left| A_n \right|^2 = \frac{1}{4b} \left| (\mathbf{B}_n + \mathbf{B}'_n) \right|^2, \tag{79}$$

where the vectors $\mathbf{B}_n$ and $\mathbf{B}'_n$ are given by

$$\mathbf{B}'_n = \pm C\left[\frac{\pi (b-n)^2}{2b}\right] \pm iS\left[\frac{\pi (b-n)^2}{2b}\right], \tag{80}$$

$$\mathbf{B}_n = C\left[\frac{\pi (b+n)^2}{2b}\right] - iS\left[\frac{\pi (b+n)^2}{2b}\right],$$

and C and S are the Fresnel integrals

$$C(z) \pm iS(z) = \int_0^z \frac{e^{\pm it}}{\sqrt{2\pi t}}\, dt.$$

A qualitative picture of the relative magnitudes of A_n as a function of the modulation index b and the sideband order n may be obtained at once by considering a modification of Cornu's spiral

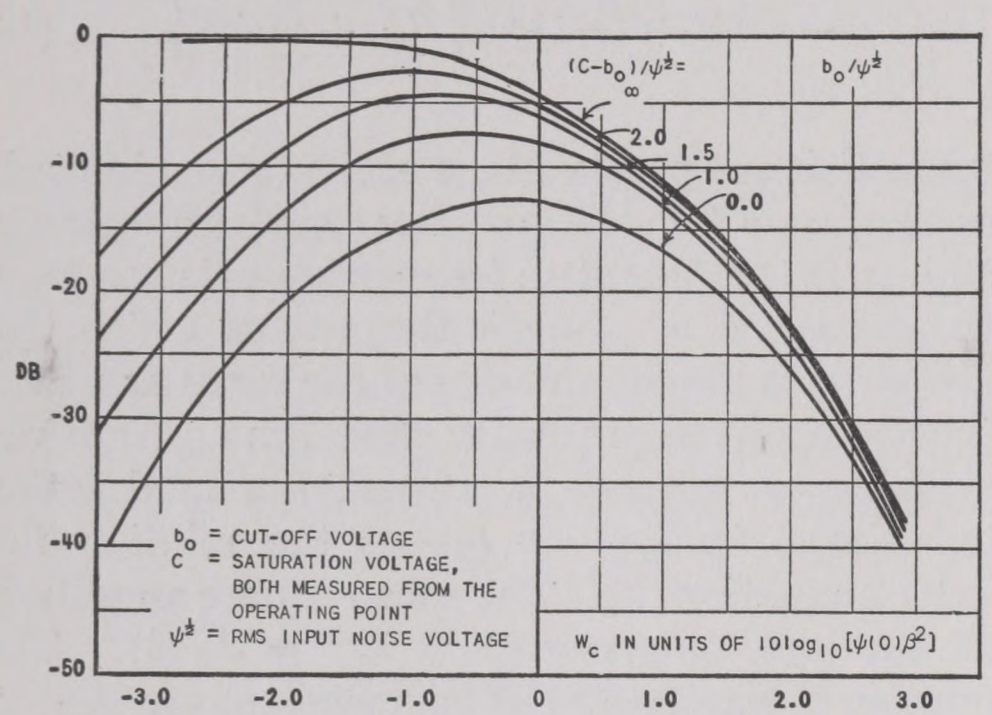


FIGURE 15. Power in the continuum after rectification and clipping of the input noise by a biased and saturated linear rectifier.

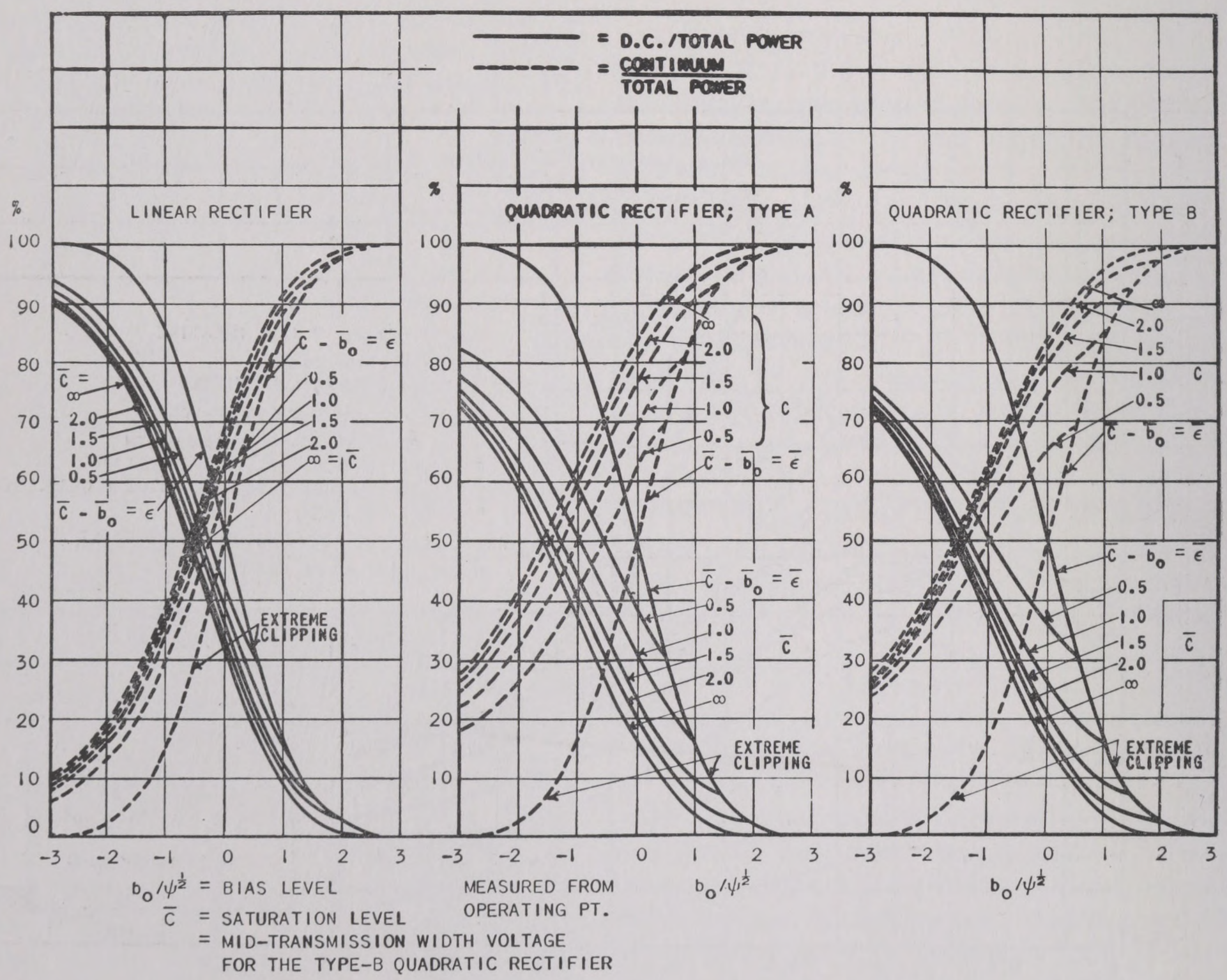


FIGURE 16. A comparison of the percentage of the total output in the d-c and continuum, after linear or quadratic rectification.

shown in Figure 19. For large b, and consequently large values of $(b \pm n)^2\,\pi/2b$, the vectors $\mathbf{B}_n$ and $\mathbf{B'}_n$, with their terminations on the spiral as shown in Figure 19, circle around the point J in ever decreasing spirals as $\pi(b \pm n)^2/2b$ increases, provided $(b-n) > 0$. When $(b-n) < 0$, $\mathbf{B}_n$ circles around J'. The resultant of the two vectors is large for $(b - n) > 0$, and is quite small for $(b - n) < 0$, becoming smaller as n increases for a given b. As n progresses through integral values, and b is large, the vector sum $\mathbf{B}_n + \mathbf{B'}_n$ oscillates somewhat but keeps a comparatively large average value, until $b < n$, whereupon the resultant decreases rapidly and approaches zero amplitude for extreme values of n. As $b \to \infty$, the spectral half-width approaches ΔF, the extent of the frequency deviation. The spectral distribution is discrete, as before, but is reasonably uniform, as can be seen from Figure 20.

"Triangular" Frequency Modulation. For frequency modulation by a symmetrical sawtooth wave (3), the mean-square amplitude of the nth component is

$$\left| A_n \right|^2 = \left| \cos\left[\frac{\pi(b \pm n)^2}{4b} \right] \right| \left| \mathbf{B}_n + \mathbf{B}'_n \right|, \qquad (81)$$

and here again the vector diagram, Figure 19, may be applied to show how the magnitude of each component changes as n increases. The effect of the trigonometric factor in equation (81) is to cause a fluctuation in the length of the vector resultant shown in Figure 19, a fluctuation which is rapid for small values of the modulation index b, small n, and which becomes more rapid as n is increased. Moreover, as b is made larger, the oscillations also become more rapid. This is the analytical reason why the spectra of the sawtooth and symmetrical sawtooth frequency modulation differ so much in character, as seen in Figure 20.

Square-Wave Frequency Modulation. The problem of frequency modulation by a square wave has been solved,[844] the resulting expression for the modulated wave being:

The mean-square amplitude of the nth component is

$$|\, A_n \,|^2 = \frac{4b^2}{\pi^2} \frac{\sin^2 \frac{\pi(b-n)}{2}}{(b^2 - n^2)^2}. \qquad (83)$$

For large modulation indices, and of course constant deviation ΔF, the energy of the original carrier is observed to be concentrated more and more in two pairs of sidebands, a pair on either side of the carrier and approximately the half bandwidth ΔF from it. When the sweep is very slow, corresponding to $b \to \infty$, each pair becomes a single, discrete sideband at $\pm\Delta F$ from f_c. This is understandable from a physical point of view, since in the limiting case $b \to \infty$, the signal energy is present at $f_c + \Delta F$ half the time, and at $f_c - \Delta F$ the other half, and the amount of energy at a given frequency is proportional to the time the wave spends at that frequency.

Conclusions from the Study

With the above analytical details in mind, it was possible to outline the requirements of a possible use of frequency modulation in conjunction with amplitude modulation or frequency modulation by noise[525] for barrage jamming radar or communications systems. Frequency modulation was to be used to provide as wide and as uniform a barrage as possible. These requirements are outlined briefly as follows.

1. *Proper spacing between f-m sidebands.* For radar jamming, the minimum permissible sideband separation f_0 should not be less than about one-half the effective video bandwidth of the receiver being jammed. For communication jamming about one-half to one-fifth the audio bandwidth was suggested. The maximum permissible separation should be about one-fifth or one-sixth the half barrage width ΔF.

2. *Spectral uniformity.* Spectral uniformity should be obtained with reasonable satisfaction for radar jamming if the half barrage width lies between a lower limit of about 5 times and an upper limit of at most about 25 times the f-m sweep rate f_0. For communications jamming the

---

$$E(t) = \frac{2}{\pi} \hat{E}_c \left\{ \frac{\sin \frac{\pi b}{2}}{b} \cos \omega_c t + \sum_{n=1}^{\infty} \frac{(-1)^n b}{b^2 - n^2} \sin \frac{\pi(b-n)}{2} \left[\cos(\omega_c t - n\omega_0 t) + (-1)^n \cos(\omega_c + n\omega_0)t \right] \right\}. \qquad (82)$$

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half barrage width may be from fifty to several thousand times the sweep frequency.

3. *Type of frequency modulation used.* For radars, either sinusoidal frequency modulation or symmetrical sawtooth frequency modulation was suggested. (However, a sawtooth wave is preferable spectrally, if practicable at these frequencies.) For communications, symmetrical sawtooth frequency modulation should be used; sawtooth frequency modulation is again to be preferred, if obtainable.

4. *Modulation index:* $b = \Delta F/f_0$. For radar work, 5, 6, $< b <$ 25; for communications, we have $50 \backsim b \backsim 3{,}000$. The limits on the modulation index vary with the receiver characteristics. The width of the band of noise amplitude modulation or frequency modulation that is used with the various types of periodic frequency modulation to "fill in" the spectrum should be about three-fourths the sideband separation f_0, so that holes in frequency will not occur.

Jittered Frequency Modulation

Some effort was also made to investigate the effect on the response of a detector to "jittered," slow frequency modulation.[631] The work is of interest primarily in connection with communication jamming. It considered the character of the response of a receiver to a superposition of slow, regular, periodic (e.g., mechanical) frequency modulation of wide deviation and a jittering or noise frequency modulation of smaller swing. The spectrum was found to consist of two parts: a continuous background and a discrete portion confined to frequencies (measured

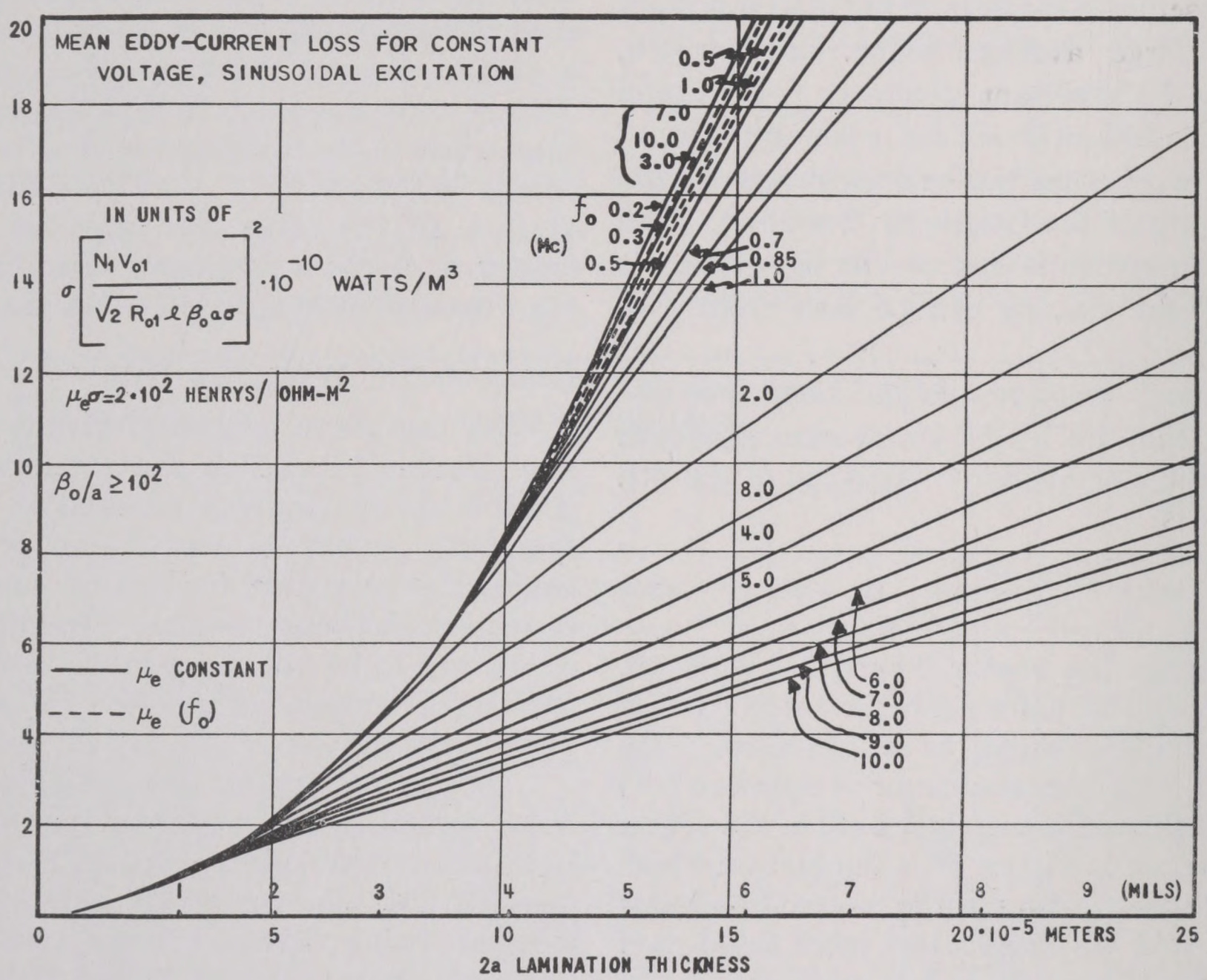


FIGURE 17. Mean eddy-current loss (per unit volume) for constant voltage transformers excited by a sine wave.

relative to the carrier as origin) which are multiples of the slow-scanning frequency. Presumably, the discrete portion should be minimized, as it excites only certain nerves of the ear. It is observed that half of the energy lies in the continuum (the best obtainable fraction), if the jittering has sufficient rapidity and amplitude

Simultaneous Frequency Modulation and Amplitude Modulation

One further problem of some interest that was examined briefly[373] concerned the presence of simultaneous frequency and amplitude modulation in the output of self-excited, u-h-f oscillators.

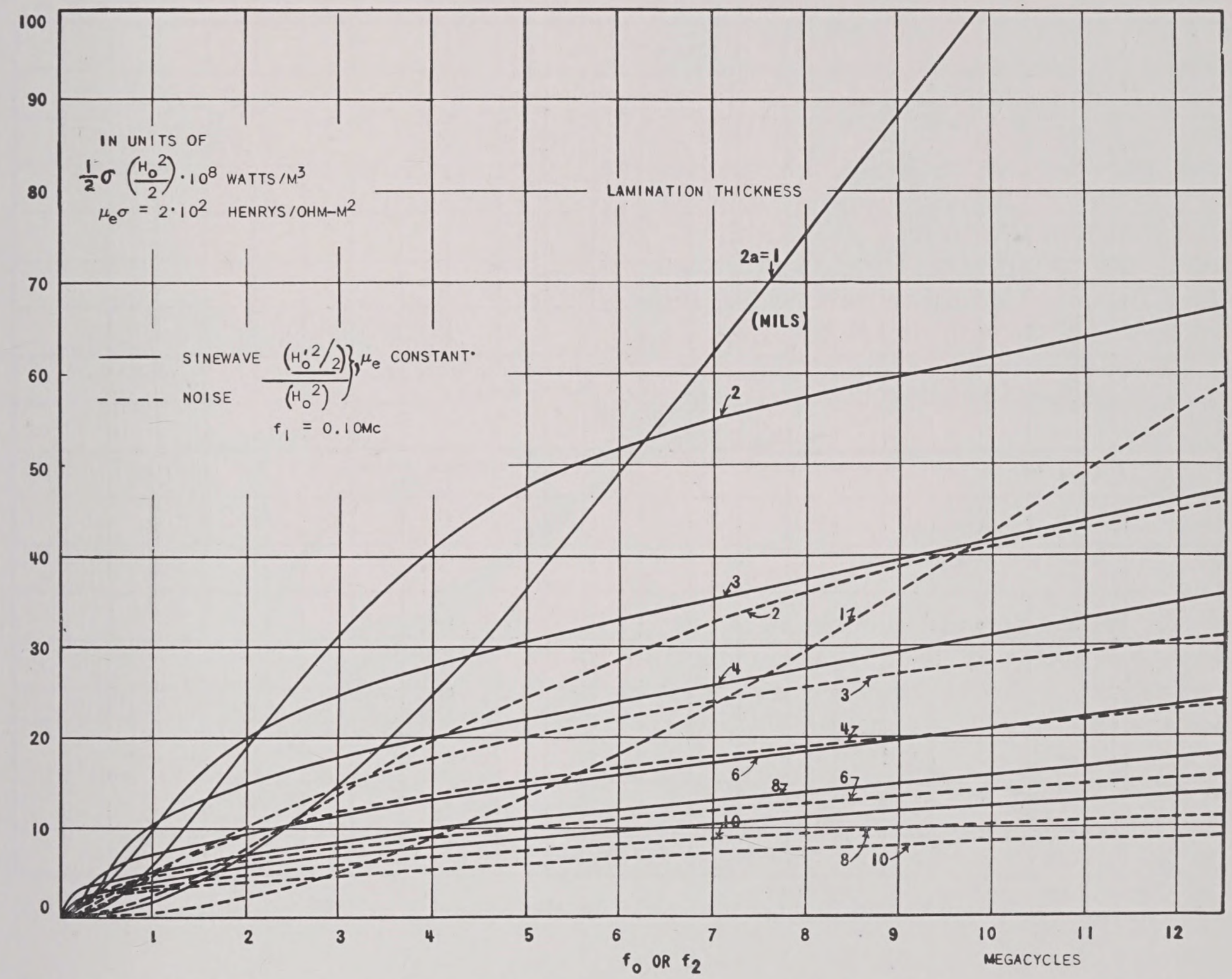


FIGURE 18. Mean eddy-current loss (per unit volume) for random noise with constant mean-square input voltage and a uniform spectrum.

so that a receiver is traversed by the frequency several times per half-scanning period. Instead of several traversals per scan, it is also sufficient if there is enough jittering so that the traversal time varies materially from scan to scan. The mathematical model used in the analysis of the problem is that of a square rectifier exposed to a collection of random pulses.

To gain an approximate understanding of the operation of such tubes, an idea of the magnitude of the frequency modulation and its phase relation to the amplitude modulation is desirable. In practice, this may be best achieved by measurement of the spectrum when the oscillator is amplitude-modulated a fixed percentage by a sine wave of known frequency. By matching

the experimental voltage spectrum with the calculated one, in cut-and-try fashion, the degree of incidental frequency modulation may be determined.

6.3 TRANSMISSION AND REFLECTION OF ENERGY

When radar or jamming signals are used, energy is ultimately propagated through space in the form of electromagnetic waves, which strike targets and are reflected by them, with a resulting measure of information (or lack of it, depending on the nature of the transmitted wave). For radar signals, the echoes convey certain intelligence; in jamming, this intelligence is partly or completely destroyed. In the sections above, some of the theory behind "active" or electronic jamming has been discussed; but there is another large and effective field of countermeasures to be considered—"passive" jamming, which seeks to invalidate the enemy's radar and communication systems through his own emitted signals. The basic idea is to introduce a device or devices which reflect the original wave in a confused and heterogeneous manner, thus negating any information which might be reflected. A large and important class of passive jammers used in RCM falls under the general heading of "confusion reflectors" (Window),

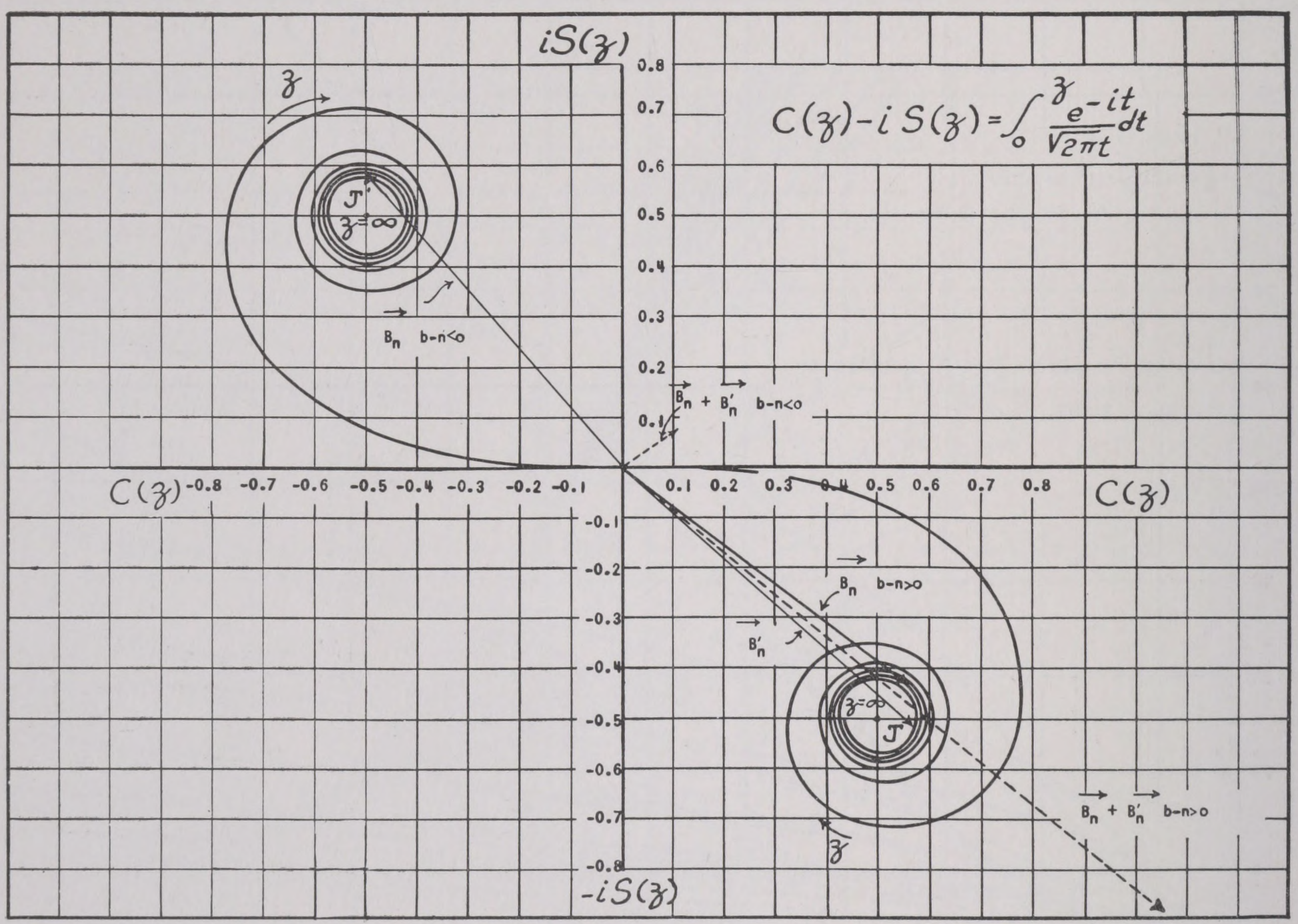


FIGURE 19. Cornu's spiral for the vectors $\mathbf{B}_n$ and $\mathbf{B}'_n$.

whose theoretical characteristics are outlined below. A discussion of the practical details of the design and use of Window is given in Chapter 12.

6.3.1 Studies of Reflectors

Window is a term designating passive jammers whose purpose is to reflect and return transmitted radar signals in a random fashion, so that the echo pips are distorted and without distinguishing features.[499] This can be accomplished by "sowing" suitably designed conductors in the

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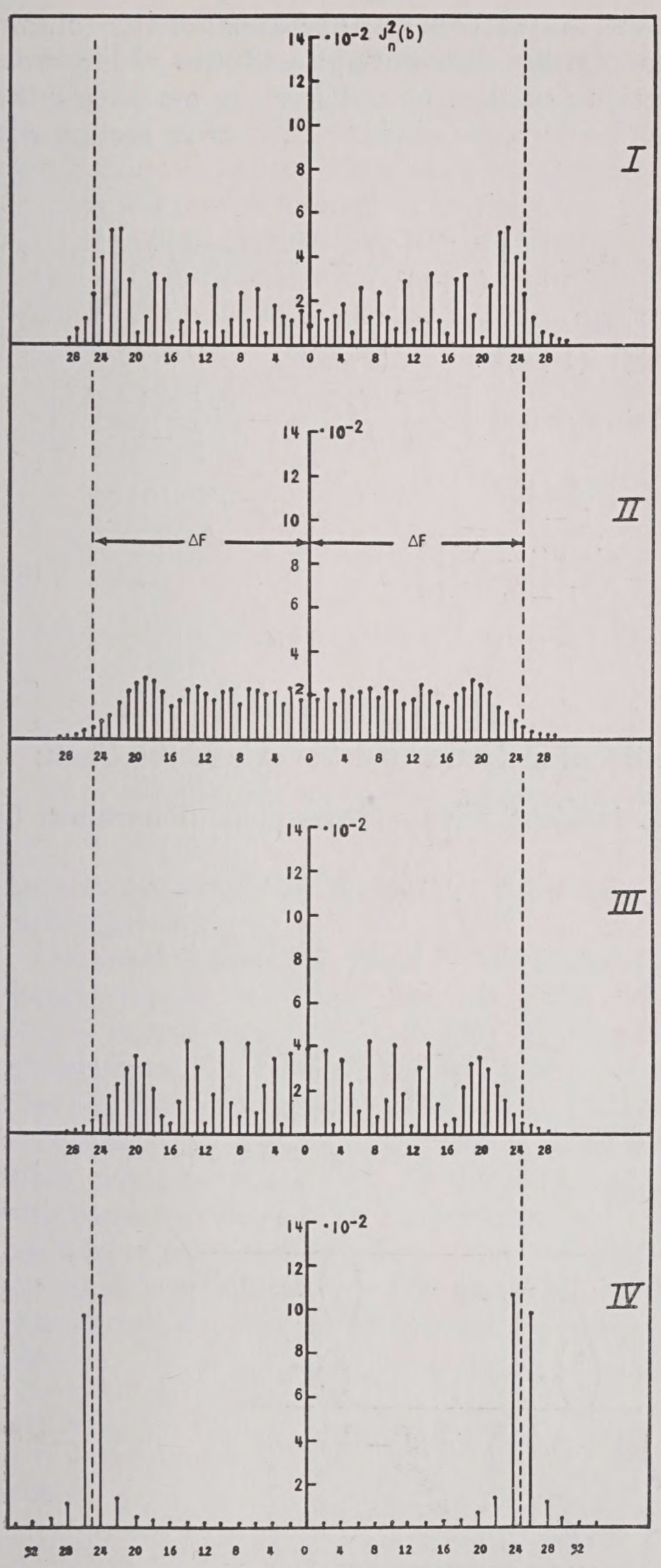


FIGURE 20. A comparison of four different types of frequency-modulation spectra. Type I is frequency modulation by sine wave, Type II by unsymmetrical sawtooth wave, Type III by symmetrical sawtooth wave, and Type IV by square wave.

area or region to be concealed—either in the form of thin metal strips, or as long reflecting strands of metal, or in the form of corner reflectors. In this section, the theoretical methods and results concerning Window response are outlined.

CHAFF

The design of Chaff (see Section 12.2.1) for countermeasures poses several problems, including the questions of (1) the optimum dipole length for producing echoes at a given frequency, (2) the magnitude of the frequency band over which a particular dipole produces an appreciable echo, (3) the dependence of the radar response of Chaff on its cross-sectional dimensions, and (4) the effect of Chaff designed for one frequency at other bands in use for radar.

The analysis is simplified considerably if the cross-sectional dimensions are small compared with the radar wavelength λ. The Chaff can then be considered to be a circular cylinder of "equivalent radius" a. For Chaff in the form of a flat strip of width d, the equivalent radius[477] is given by

$$a = \frac{d}{4}. \tag{84}$$

If the cross-sectional dimensions are not small compared to λ, then the response depends strongly on the exact cross-sectional shape. A detailed analysis of Chaff response was carried out.[602]

The electric field of the incident radar beam induces currents in the Chaff. Once this induced current distribution is known, the field produced by it in the direction of the transmitter can be computed and the radar cross section can be evaluated. The determination of the induced currents can be made in several ways.

Approximate "Engineering" Procedure. Here one makes a judicious guess as to the form of the current distribution; for example, in the case of resonant dipoles one may assume a sinusoidal current which vanishes at the ends of the dipole. The amplitude of the current can then be fixed by applying the principle of conservation of energy.

Solution of the Field Equations. If it is assumed that the Chaff material is a perfect conductor, then the tangential component of the total elec-

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tric field (incident + scattered field) must vanish at the surface of the Chaff. The mathematical formulation of this statement gives an integral equation for the current distribution induced in the Chaff. This integral equation can then be solved by successive approximations to obtain the current distribution; and the radar cross section can then be obtained by evaluating the flux back to the radar.[602] The cross section σ is given by

$$\sigma = \frac{4\lambda^2}{\pi}\cos^4\phi\left\{[F'^2+F''^2]\left[\frac{\sin 2xy}{2y}\right]^2+[G'^2+G''^2]\cos^2 xy\left[\frac{\sin^2 x(1+y)}{(1+y)^2}+\frac{\sin^2 x(1-y)}{(1-y)^2}\right.\right.$$
$$\left.+\frac{2\sin x(1-y)\sin x(1+y)}{1-y\qquad 1+y}\right]+[H'^2+H''^2]\sin^2 xy\left[\frac{\sin^2 x(1+y)}{(1+y)^2}+\frac{\sin^2 x(1-y)}{(1-y)^2}\right.$$
$$\left.-\frac{2\sin x(1-y)\sin x(1+y)}{(1-y)\ (1+y)}\right]+2[G'H'+G''H'']\sin xy\cos xy\left[\frac{\sin^2 x(1+y)}{(1+y)^2}-\frac{\sin^2 x(1-y)}{(1-y)^2}\right]$$
$$+2[F'G'+F''G'']\cos xy\,\frac{\sin 2xy}{2y}\left[\frac{\sin x(1+y)}{1+y}+\frac{\sin x(1-y)}{1-y}\right]$$
$$\left.+2[F'H'+F''H'']\sin xy\,\frac{\sin 2xy}{2y}\left[\frac{\sin x(1+y)}{1+y}-\frac{\sin x(1-y)}{1-y}\right]\right\}, \tag{85}$$

where $x = \frac{2\pi l}{\lambda}$, $2l$ = length of Chaff;

$y = \cos\ \Theta$, Θ = angle between the direction of incidence and the axis of the Chaff;

ϕ = angle between the electric field of the incident wave and the plane determined by the dipole and the direction of incidence;

$\beta = \frac{2\pi}{\lambda}$, a = equivalent radius of the Chaff,

$$F' = \frac{\Omega'}{\Omega'^2}+\pi^2,\ F'' = \frac{\pi}{\Omega'^2}+\pi^2,$$

$$\Omega' = 2\log\left(\frac{\lambda}{\pi a}\right)-1.154,$$

$$2G' = \frac{-(\Omega'-\Delta)\cos\beta l+\left(\frac{\pi}{4}\right)\sin\beta l}{[\,(\Omega'-\Delta)\cos\beta l-\left(\frac{\pi}{4}\right)\sin\beta l\,]^2+[\,\tfrac{1}{2}(\log 4\beta l+0.577)\sin\beta l-\left(\frac{\pi}{4}\right)\cos\beta l\,]^2}-\pi\frac{G''}{\Omega'},$$

$$2G'' = \frac{\tfrac{1}{2}(\log 4\beta l+0.577)\sin\beta l-\left(\frac{\pi}{4}\right)\cos\beta l}{[\,(\Omega'-\Delta)\cos\beta l-\left(\frac{\pi}{4}\right)\sin\beta l\,]^2+[\,\tfrac{1}{2}(\log 4\beta l+0.577)\sin\beta l-\frac{\pi}{4}\cos\beta l\,]^2},$$

$$2H' = \frac{-(\Omega'-\Delta)\sin\beta l-\frac{\pi}{4}\cos\beta l}{[\,(\Omega'-\Delta)\sin\beta l+\frac{\pi}{4}\cos\beta l\,]^2+[\,\tfrac{1}{2}(\log 4\beta l+0.577)\cos\beta l+\frac{\pi}{4}\sin\beta l\,]^2}-\frac{\pi H''}{\Omega'},$$

$$2H'' = \frac{-[\,\tfrac{1}{2}(\log 4\beta l+0.577)\cos\beta l+\frac{\pi}{4}\sin\beta l\,]}{[\,(\Omega'-\Delta)\sin\beta l+\frac{\pi}{4}\cos\beta l\,]^2+[\tfrac{1}{2}(\log 4\beta l+0.577)\cos\beta l+\frac{\pi}{4}\sin\beta l\,]^2},$$

$\Delta = -(\frac{1}{2}\log\beta l+0.288-1)$.

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If the Chaff is assumed to be oriented at random,[479] the averaged cross section $\bar{\sigma}$ is given by

$$\begin{aligned}\frac{16\pi\bar{\sigma}}{3\lambda^2} &= (F'^2 + F''^2)(2\pi x - 1) + (G'^2 + G''^2)\cdot \\ &[2\pi x + 8x \log 2 (\sin x \cos x) - 1 \\ &+ \tfrac{1}{2}(\cos^2 x - \sin^2 x) + \pi \sin 2x \\ &- 2\cos 2x(\log 4x + 0.577) + (\log 4x + 0.577) \\ &+ (\sin^2 2x - \cos^2 2x)\log 2] + (H'^2 + H''^2)\cdot \\ &[2\pi x - 8x \log 2 (\sin x \cos x) - 1 \\ &- \tfrac{1}{2}(\cos^2 x - \sin^2 x) - \pi \sin 2x \\ &+ 2\cos 2x (\log 4x + 0.577) + \log 4x + 0.577 \\ &+ (\sin^2 2x - \cos^2 2x)\log 2] \\ &+ 2(G'H' + G''H'')\cdot \\ &[4x(\cos^2 x - \sin^2 x)\log 2 - \sin x \cos x] \\ &+ 4(F'G' + F''G'')\left[\frac{7}{4}\pi \sin x\right. \\ &\left. - \tfrac{1}{2}\cos x(\log 4x + 0.577) - \tfrac{1}{2}\log 2 (\cos 3x)\right] \\ &+ 4(F'H' + F''H'')\left[\frac{\pi}{4}\cos x\right. \\ &\left. - \tfrac{1}{2}\sin x (\log 4x + 0.577) + \tfrac{1}{2}\log 2 (\sin 3x)\right]. \end{aligned} \tag{86}$$

As can be seen, the theoretical equations are rather forbidding.

Conclusions from the Theory. On elementary theory the current will become large when $4l/\lambda = m$, where $m = 1, 2, 3$, etc. In this case of resonance, the cross section will also be large. The equations given above show that the resonances occur at slightly longer wavelengths than those given by $\lambda = 4l/m$. As the radius of the wire increases, there is an increasing shift in the position of the resonance from $4l/m$, its position for vanishing radius.[602] The position of the resonance is determined by solving the equation:

$$\begin{matrix}\text{odd res.} \\ m = 1, 3, 5 \ldots \\ \text{even res.} \\ m = 2, 4, 6 \ldots\end{matrix} \begin{pmatrix} \cot \beta l \\ -\tan \beta l \end{pmatrix} = \frac{\pi}{4(\Omega' - \Delta)}(1 + \epsilon), \tag{87}$$

where

$$\epsilon = \frac{\left(\log \frac{8\pi l}{\lambda} + 0.577\right)^2 + 2\left(\log \frac{8\pi l}{\lambda} + 0.577\right)(\Omega' - \Delta)}{[\,2(\Omega' - \Delta)\,]^2}.$$

As an example, for $2l/a = 900$ the resonances occur for $4l/\lambda = 0.95, 1.94, 3.93, 4.925$.

Figures 21 and 22 show the dependence of $\bar{\sigma}$ on $2l/a$ and $2l/\lambda$ over a wide range of values of the parameters.

The *unaveraged* σ depends on θ. Figures 23 to 26 are examples of the angular patterns. A study was made of Chaff response as a function of polarization and angle of elevation.[478]

The simple theory gives $\bar{\sigma}/\lambda^2 = 0.153$ independent of $2l/a$. The more detailed theory gives

$$\frac{\bar{\sigma}}{\lambda^2} = 0.184, 0.194, 0.204$$

for $\frac{2l}{a} = 900, 450$, and 225, respectively.

Rope

Rope consists of streamers (see also Section 12.2.1) whose length L is large compared to ordinary radar wavelengths λ, and is generally made in the form of flat strips of width d. The random deviations of the Rope during its fall permit only small fractions of its length to scatter coherently. This results in eliminating any strong dependence of the cross section on the orientation of the Rope.[451, 452]

For Rope whose cross-sectional dimensions are small compared to λ, use may be made of the concept[477] of equivalent radius a. In this case ($\lambda >> a$), the response to a wave polarized perpendicular to the length of the Rope is negligible. For a field parallel to the Rope axis the cross section[451] is given by

$$\sigma = \frac{\frac{KL\lambda}{2}}{\left(\frac{\log \lambda}{\pi\gamma a}\right)^2 + \frac{\pi^2}{4}}, \quad \gamma = 1.781, \tag{88}$$

where K is a constant determined by the deviations of the Rope from a straight line.

If the cross-sectional dimensions of the Rope are not small compared to λ, the theory becomes complicated.[452] For a ribbon-shaped Rope of width d, the cross section can in general be expressed as:

$$\sigma = KAf(c), \tag{89}$$

where $A = Ld$ is the area of the ribbon and $c = \pi d/\lambda$. The solution of the scattering problem was obtained numerically. For $c << 1$ (i. e., $\lambda >> \pi d$) the results agree with equation (88). If d is not small compared to λ, radiation polarized perpendicular to the axis of the Rope is also scattered appreciably. In fact, for large d ($d >> \lambda$) the cross section is independent of the polarization and is given by the expression for the cross section of a flat sheet. For perpendicular polarization the Rope may be considered

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to be made up of infinitely many infinitesimal dipoles oriented across the Rope. When $d = \lambda/2$, it may be expected that these dipoles will show a resonant response. The strong coupling between neighboring dipoles makes the maximum broad and not very pronounced. The cross section of Rope as a function of wavelength is shown in Figure 27. As can be seen from this figure, Rope responds strongly over wide frequency bands. Its use is especially desirable at lower frequencies where Chaff becomes inconveniently long.

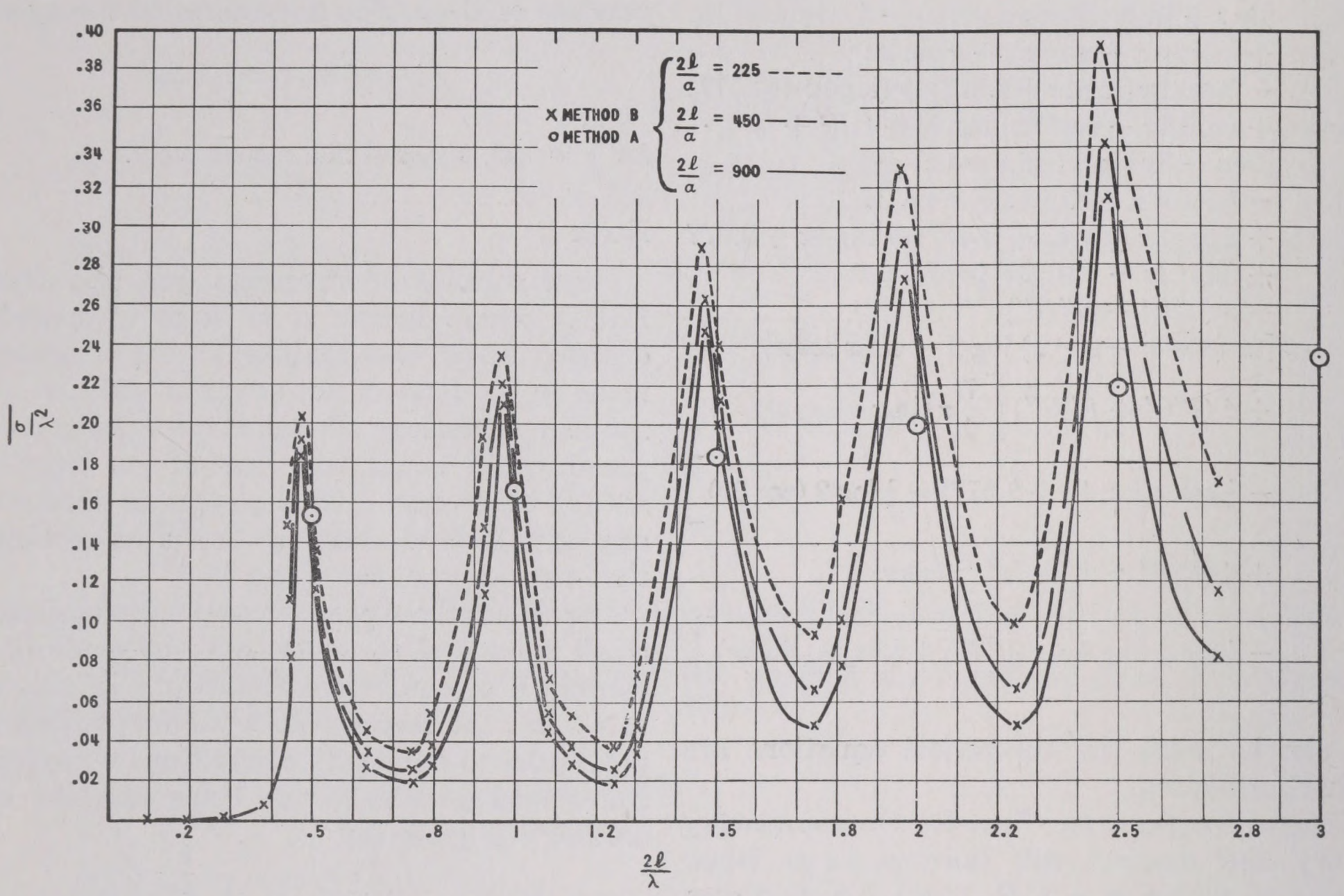


FIGURE 21. Frequency response of Chaff; average cross section.

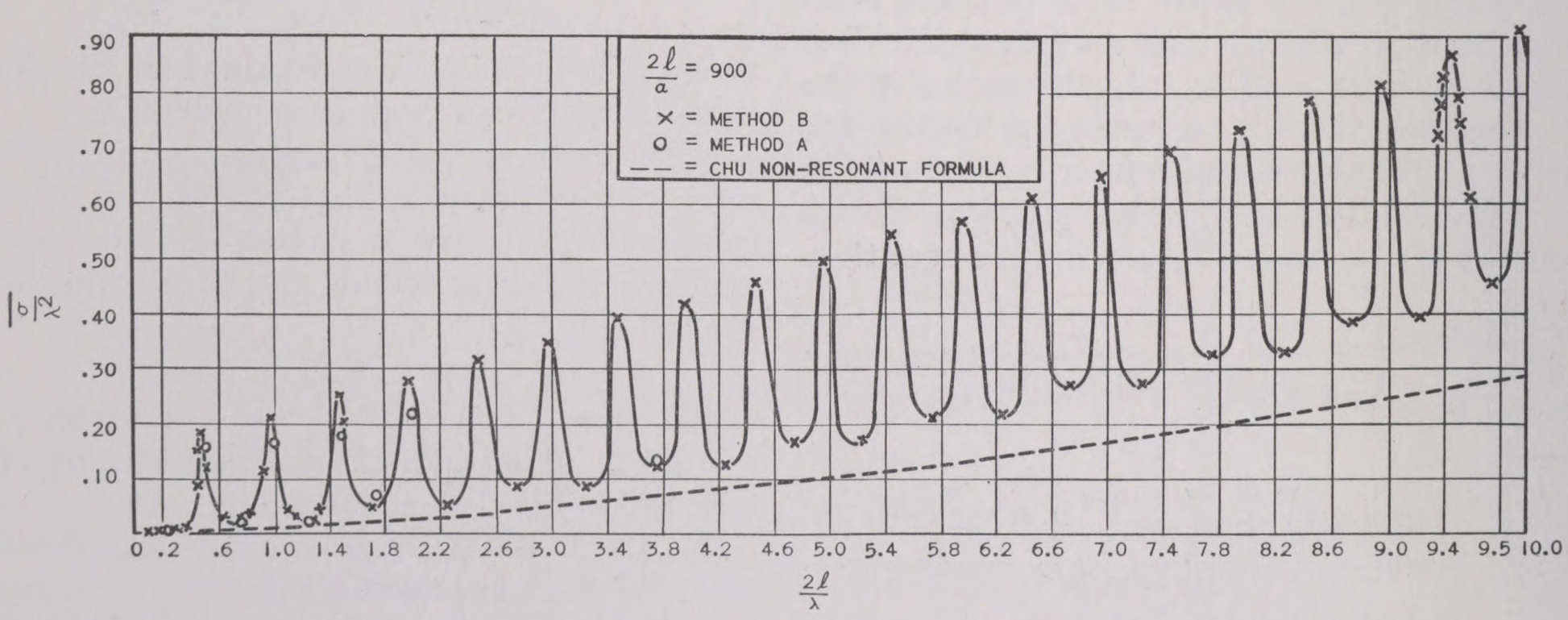


FIGURE 22. Average response of Chaff.

[redacted]

"Tuned" Rope (a series of dipoles tied together) had little application. A crude theory was developed[375,839,840] for the case where the individual dipoles of the Rope are resonant to the radar frequency. Only the interaction of nearest neighbors was considered; this gives rise to a mutual impedance term which alters the gain of the individual dipoles. Then the scattering of the individual dipole sources was computed as in the case of an optical grating. The cross section of the tuned Rope depends on the spacing s between dipole centers. It reaches a maximum for

$$s = 0.8\lambda. \tag{90}$$

However, the dependence of cross section spacing is not critical. The cross section of a tuned Rope with optimum spacing can be compared to that of a "continuous" Rope of the same length. It was found that

$$\frac{\sigma_{\text{tuned}}}{\sigma_{\text{continuous}}} \simeq \frac{0.87\lambda}{d}, \tag{91}$$

where d is the width of the strip. Thus tuned Rope is much more effective (*at resonance*) than continuous Rope. The effects of detuning from resonance, however, probably cause large holes in the frequency coverage; thus tuned Rope is more useful for beacon and identification use (fixed, known frequency) than for countermeasures.

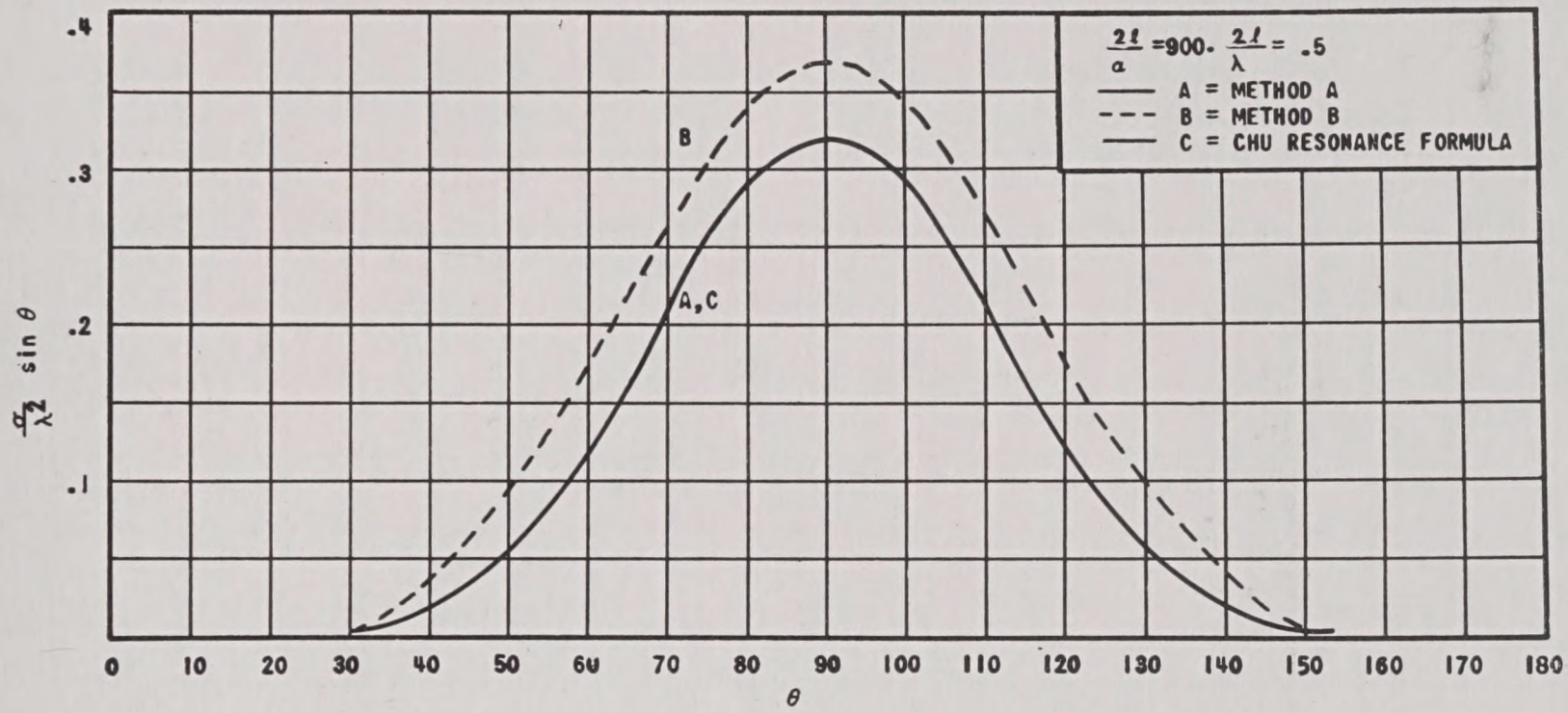


FIGURE 23. Angular distribution of the response of Chaff ($2\,l/\lambda = 0.5$).

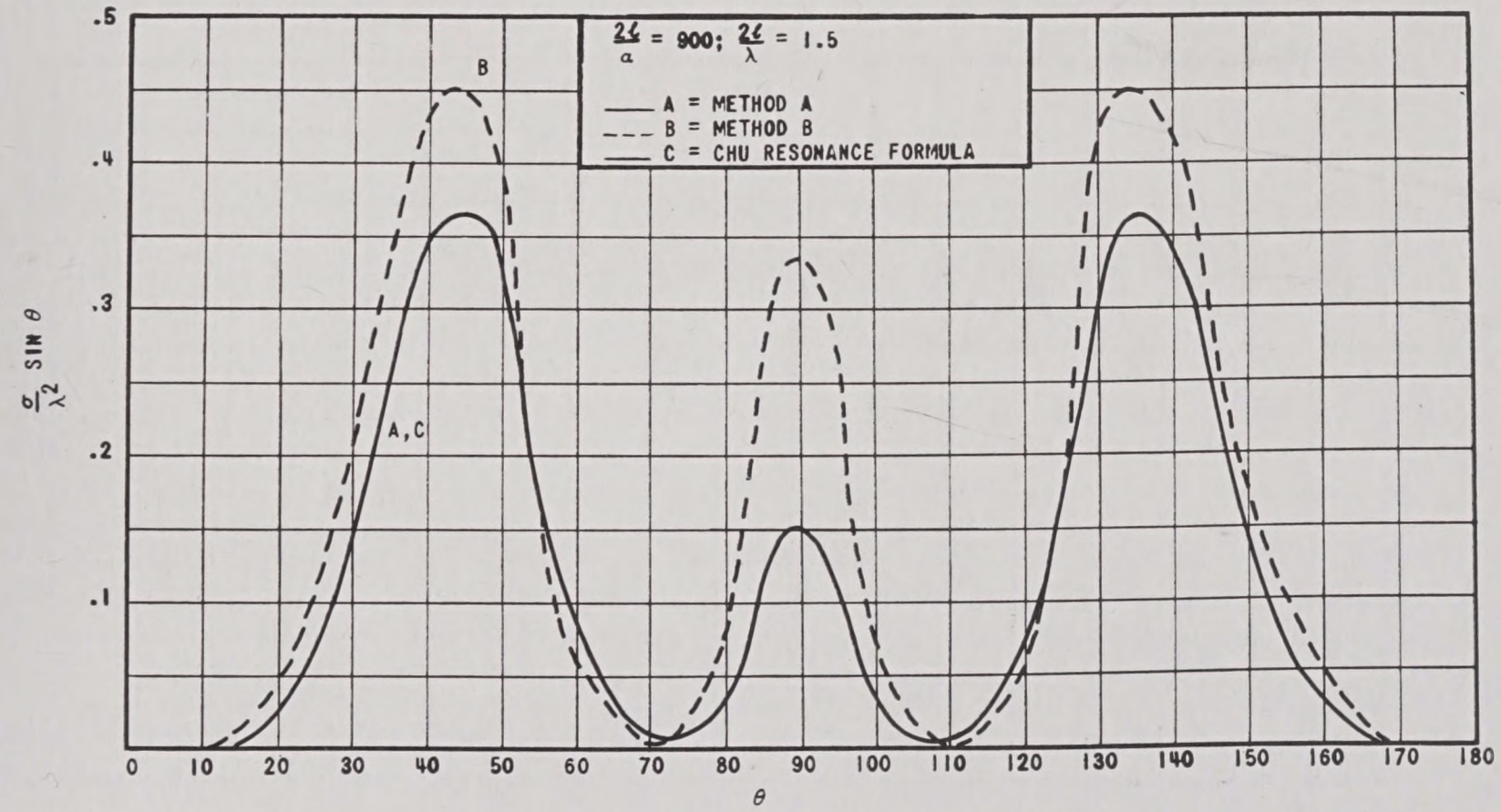


FIGURE 24. Angular distribution of the response of Chaff ($2\,l/\lambda = 1.5$).

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CORNER REFLECTORS (ANGELS)

The theory of the scattering by metallic objects composed of two ("dihedral reflector") and three (corner reflector) mutually perpendicular intersecting planes was extensively developed.[499, 841, 842] Since in practice (see Section 12.2.1) the dimensions are large compared to the wavelength, the problem was treated by the methods of geometrical optics. Kirchhoff's theory was used in estimating diffraction effects. Results are given here only for triangular-faced corner reflectors (three faces, each an isosceles right triangle of leg length l). The reflection from such a corner is a superposition of reflections from a single face, double reflections (using two faces), and triple reflections. The triple reflection predominates when $d > > \lambda$, which is the region of practical interest.

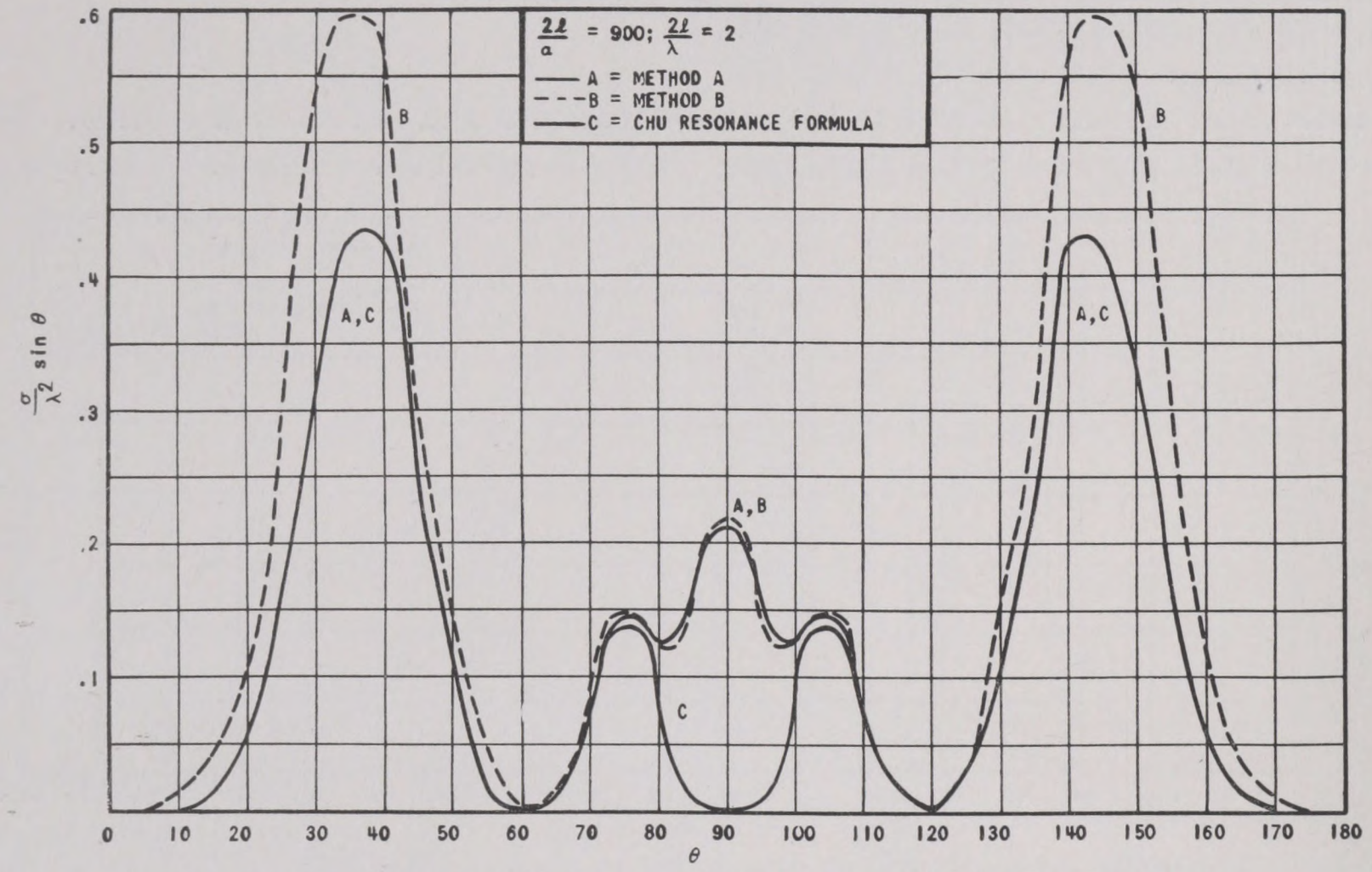


FIGURE 25. Angular distribution of the response of Chaff ($2\,l/\lambda = 2$).

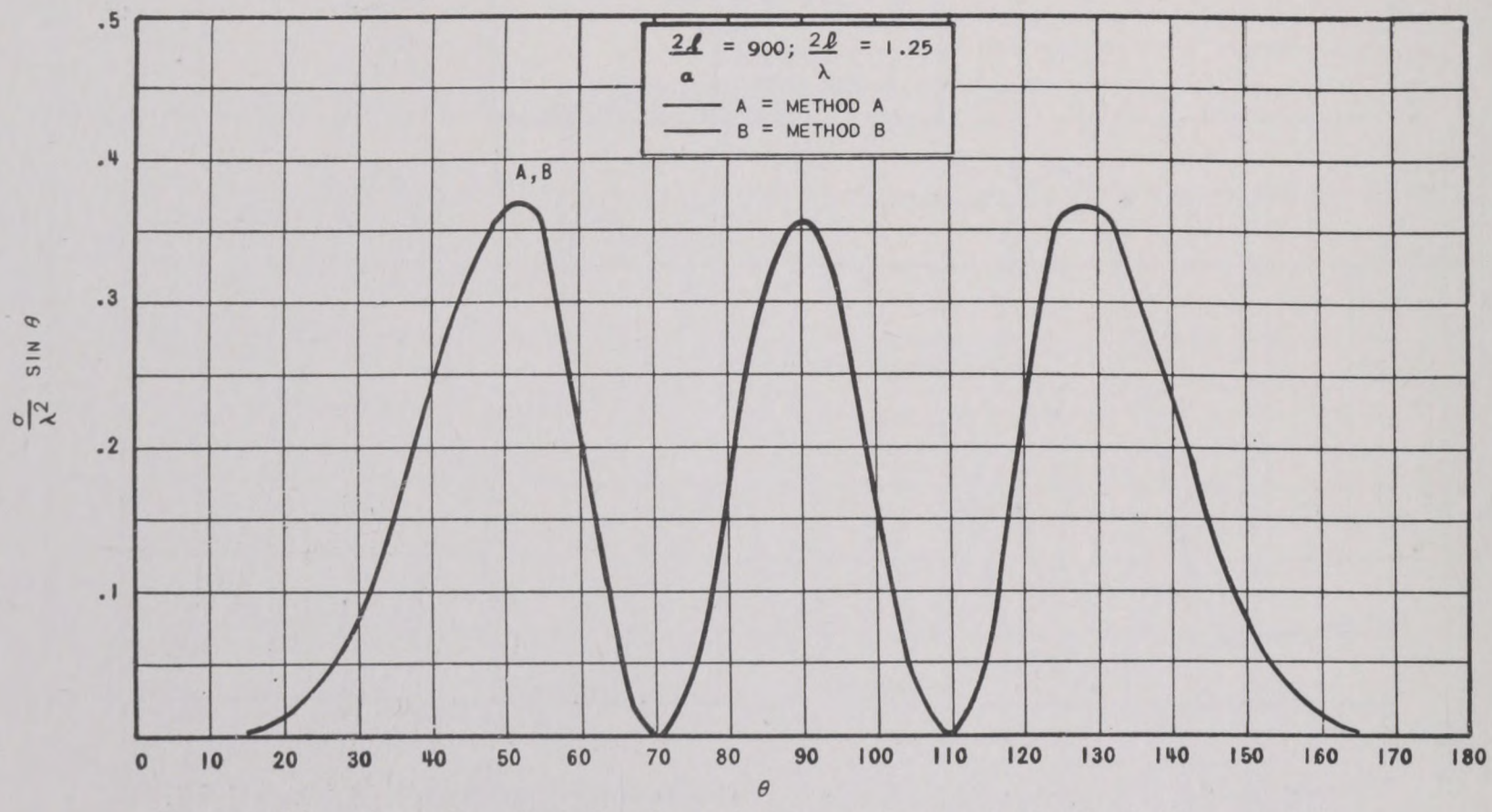


FIGURE 26. Angular distribution of the response of Chaff ($2\,l/\lambda = 1.25$).

[redacted]

The scattering by the corner reflector was shown to be given by that of a flat sheet whose area A is determined as follows. For a given direction of incidence, project both the corner and its image-in-itself on the wavefront of the incident wave. The overlapping portion of these two projections is the effective area A; the radar cross section is given by:

$$\sigma = 4\pi \left(\frac{A}{\lambda} \right)^2. \tag{92}$$

Thus for a triangular-faced corner reflector, the maximum cross section (which is obtained when the direction of incidence is the symmetry axis of the corner) becomes

$$\sigma_{\max} = \frac{4\pi}{3} \cdot \frac{l^4}{\lambda^2} \cdot \tag{93}$$

For directions other than the symmetry axis, the value of σ will decrease. If θ is the deviation (in degrees) of the direction of incidence from the symmetry axis, an approximate value for the cross section is

$$\sigma(\theta) = \sigma_{\max} (1 - 0.00076\theta^2)^2. \tag{94}$$

The values of σ given above are based on the assumption that the faces of the corner are mutually perpendicular. If the angle between any two of the faces deviates from 90 degrees, the cross section is decreased. If all three intersection angles differ from 90 degrees by an amount ϵ (in radians), the decrease in cross section is 1, 3, and 10 db for $l\epsilon/\lambda$, equal to 0.20, 0.35, and 0.62, respectively.

Anti-Window Device

Because Window, properly sown, is effective in jamming radar systems, it was deemed important to consider measures for reducing the effect of Window, so that the radar operator might obtain partial or complete information concerning his target. One such anti-Window system that was proposed utilized the difference between the fixed target echo and the random character of the Window return, for a single transmitted pulse.[630]

In general, a reduction in the pulse length results in a proportional increase in the amount of Window necessary to screen a given target. (This holds exactly only when the target is small compared with the pulse length. For targets which extend over several pulse lengths—for example, a battleship—shortening the pulse does not change the amount of Window required for screening.) The proposed method would obtain

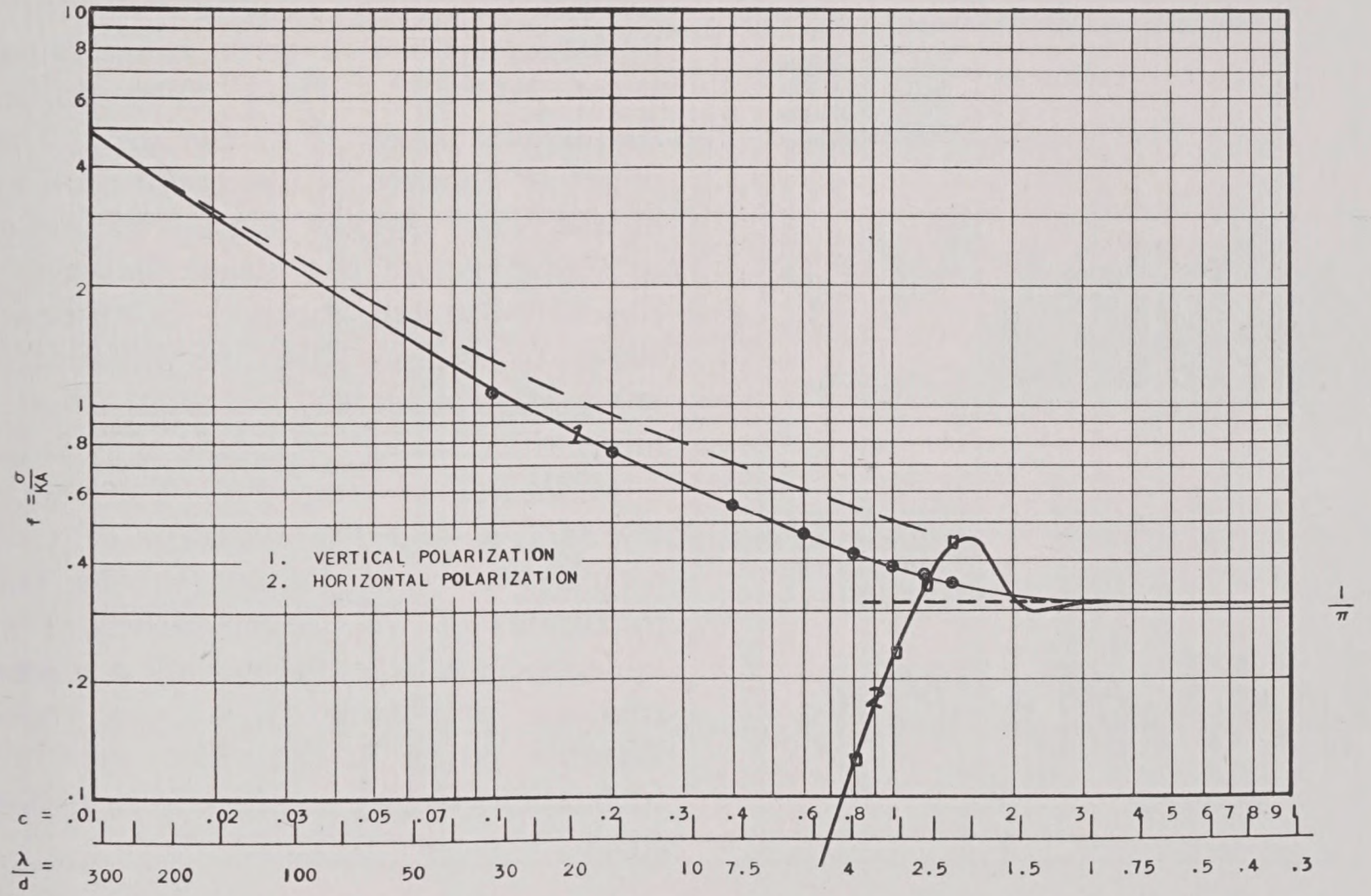


FIGURE 27. Cross section of Rope versus wavelength. Dash lines are limiting values for small and large arguments.

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the benefits of an effectively shorter pulse by means of a differentiator or some other suitable circuit, placed in the video stages of the receiver, to concentrate the target return into a pulse of duration short compared with the length of the transmitted pulse.

Without the differentiator in the circuit, the resultant of all the returns from a single transmitted pulse appears on an oscilloscope as a rectangular target echo, accompanied by the sum of a great many rectangular Window echoes, very small in amplitude, from the individual Chaff dipoles. The Window return is spread out on the screen over many pulse lengths, whereas the target echo occupies only one. After differentiation, the target return is concentrated into two intervals shorter than the pulse length, one at each end of the original rectangular pulse. On the other hand, because the Window return (for dispersed Window) consists of the random superposition of the large number of small, overlapping, dipole echoes, it remains spread out in range. Although the ratio of the power in the target echo (averaged over a pulse length or more) to that in the Window return does not change significantly, the fact that the target power is concentrated, while the Window power is not, increases the visibility of the target. The foregoing is illustrated in Figure 28.

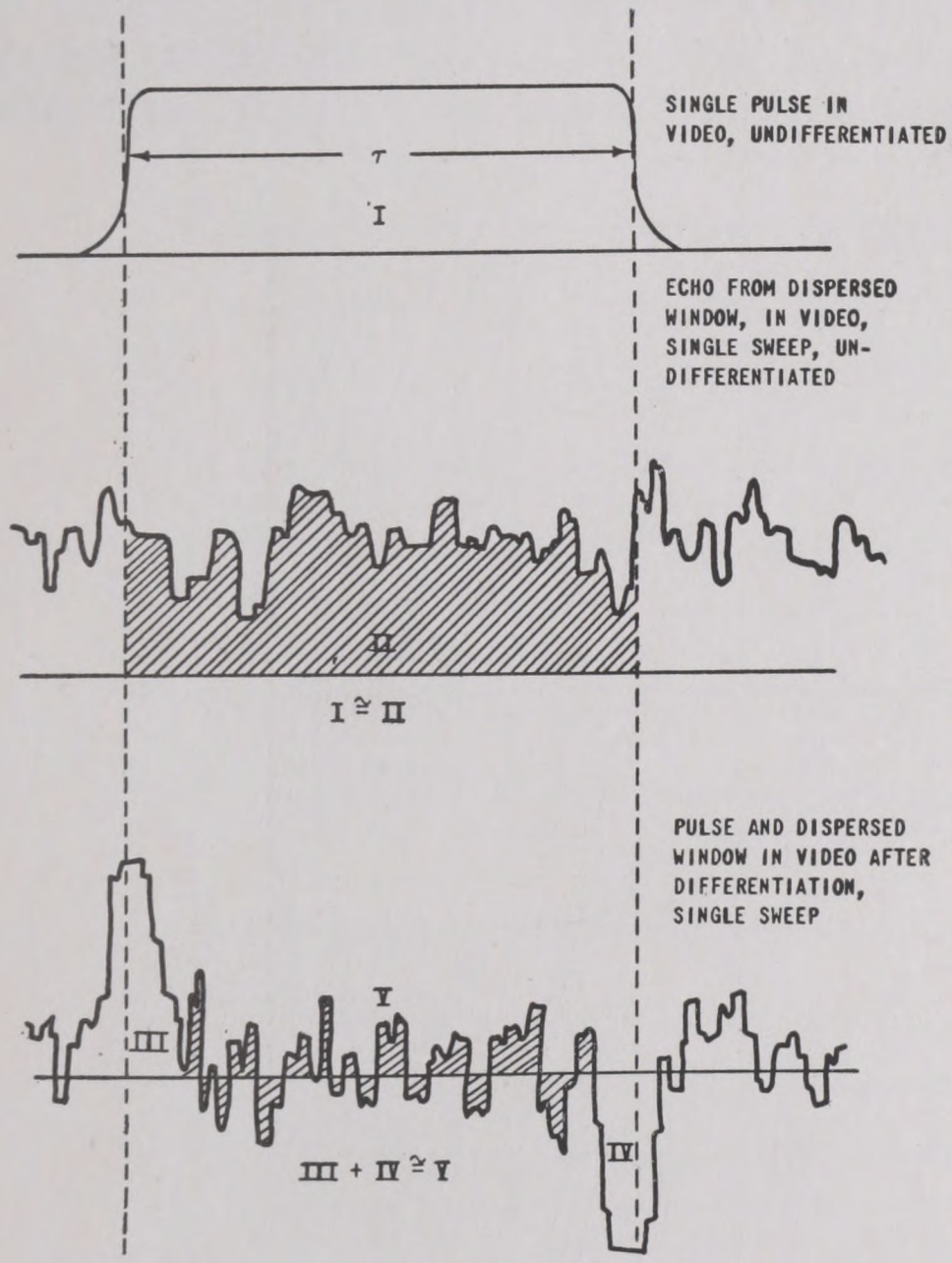


FIGURE 28. Effect of video differentation on single pulse and on Window echo. (I, II, III, etc., refer to relative power content of designated signal.)

It should be emphasized that the differentiator acts independently on the return from each single pulse—that is, on each separate sweep of the oscilloscope beam across the screen. In a normal system, the amplitude of either a Window or target echo at a given range is seen to fluctuate strongly. These fluctuations occur at frequencies lower than the prf. They are the result of changes in the orientation and spacing of the Chaff dipoles relative to one another, or in the aspect of the target, between one transmitted pulse and another—in other words, from sweep to sweep. Thus the differentiator, which reacts independently to each sweep, does not affect the relative amplitude of such fluctuations.

Mathematical Analysis. For the purpose of selecting a suitable criterion of visibility, the quantity A was defined as the ratio of the maximum of the target return, $F(t)_{\max}$, as it appears alone[k] on the oscilloscope screen, to the rms a-c amplitude (i. e., the root-mean a-c Window power in the video) of the Chaff disturbance, $(W_{\text{a-c}})^{\frac{1}{2}}$, as it appears alone on the scope:

$$A \equiv \frac{F(t)_{\max}}{(W_{\text{a-c}})^{\frac{1}{2}}}. \tag{95}$$

After differentiation the target echo has a maximum value

$$F(t)_{\max} = \frac{RCE}{\tau\pi}(x_c - \sin x_c), \quad x_c = \omega_c\tau, \tag{96}$$

where τ is the duration of the original pulse, RC is a constant whose value depends on the differentiating circuit used, while f_c is the half bandwidth of the i-f stages or the cutoff frequency of the video section of the receiver, whichever is the lesser. The quantity E is the video amplitude of the target return in the absence of Window. Figure 29 shows a typical pulse after

[k]Actually, of course, there is receiver noise present as well, but its level is assumed negligibly low compared with the Window and target levels.

SECRET

differentiation. The rms a-c Window amplitude after differentiation was found to be

$$(W_{\text{a-c}})^{\frac{1}{2}} = \frac{2\,RCE_0}{\tau\,\pi^{\frac{1}{2}}}\,(x_c - \text{Si}\,x_c)^{\frac{1}{2}}, \qquad (97)$$

$$\text{Si}\,x_c \equiv \int_0^{x_c} \frac{\sin\lambda}{\lambda}\,d\lambda,$$

where E_0 is the rms amplitude of the a-c Window component, as seen in the video stages (or, equivalently, the square root of the a-c Window power).

Chaff package remains essentially a point source, i.e., for the first minute or two from the time it is dropped, the mean power spectrum was found to be

$$W_w(f)_{\text{initial}} = 8E_0^2\,\tau\left(\frac{\sin^2\frac{x}{2}}{x^2} + \frac{1}{b}\,\frac{\sin^2\frac{bx}{2}}{x^2}\right), \quad x = \omega\tau. \qquad (99)$$

Again the first term represents the a-c spectrum and the second, the d-c. Figure 30 illustrates equations (98) and (99), as well as the spectrum

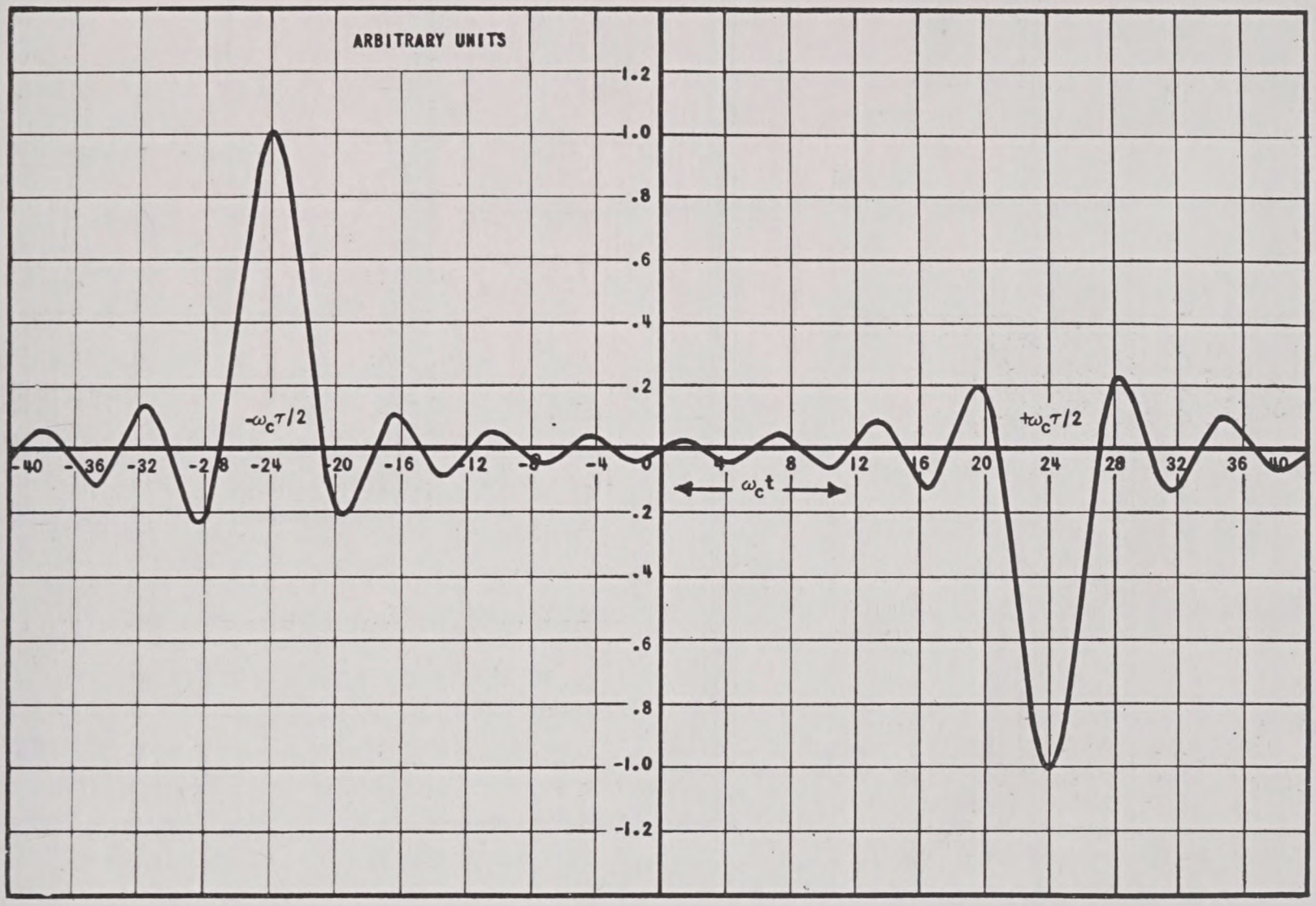


FIGURE 29. Time response of a differentiated square pulse.

The total mean power spectrum in the *steady state* of complete dispersal was seen to be

$$W_w(f)_{\text{steady state}} = 8\,E_0^2\,\tau\left[\left(1 - \frac{\sin x}{x}\right)\frac{1}{x^2} + \frac{b\sin^2\frac{x}{2}\sin^2\frac{bx}{2}}{4\left(\frac{x}{2}\right)^2\left(\frac{bx}{2}\right)^2}\right],$$

$$b \equiv T/\tau,\ x = \omega\tau = 2\pi f\tau, \qquad (98)$$

where T is the radial spread of the Chaff cloud (measured in time units for two-way transmission). The first term of equation (98) represents the a-c (or high-frequency) power and the second, the "d-c" (or slowly fluctuating) contribution to the spectrum. In the *initial state*, while the of the undifferentiated rectangular pulse, given by the following equation:

$$W_P(f) = 8E^2\tau = \frac{\sin^2\frac{x}{2}}{x^2}. \qquad (100)$$

The ratio A was then observed to take the form

$$A = \frac{1}{2\pi^{\frac{1}{2}}}\left(\frac{E}{E_0}\right)\frac{x_c - \sin x_c}{(x_c - \text{Si}\,x_c)^{\frac{1}{2}}} = \frac{A_0}{2\pi^{\frac{1}{2}}}\,\frac{x_c - \sin x_c}{(x_c - \text{Si}\,x_c)^{\frac{1}{2}}}, \qquad (101)$$

where A_0 is defined as the value of A for the unmodified receiver (i.e., without differentiator circuit), and is therefore $A \equiv E/E_0$. Figure 31 shows A as a function of $\omega_c\tau$ or $f_c\tau$, in terms of A_0.

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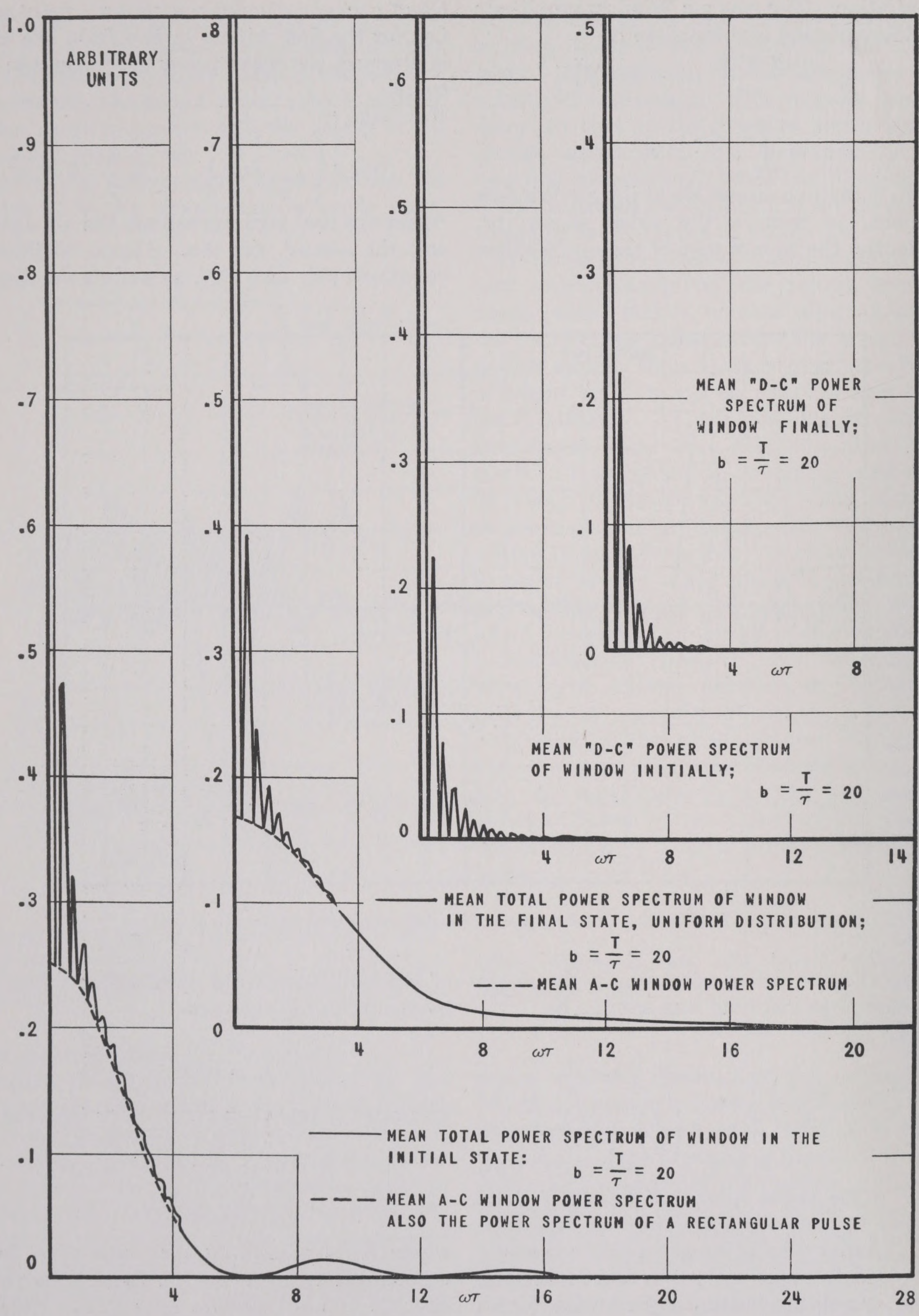


FIGURE 30. Window spectra, initially and after a condition of uniform dispersal.

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When A_0 is known, it is a simple matter to obtain $\omega_c\tau$ from the curve for the appropriate value of A. The quantity A/A_0 may be thought of as either A or A_0—that is, of the amount of Window dropped.

Summary of Results. The general results of

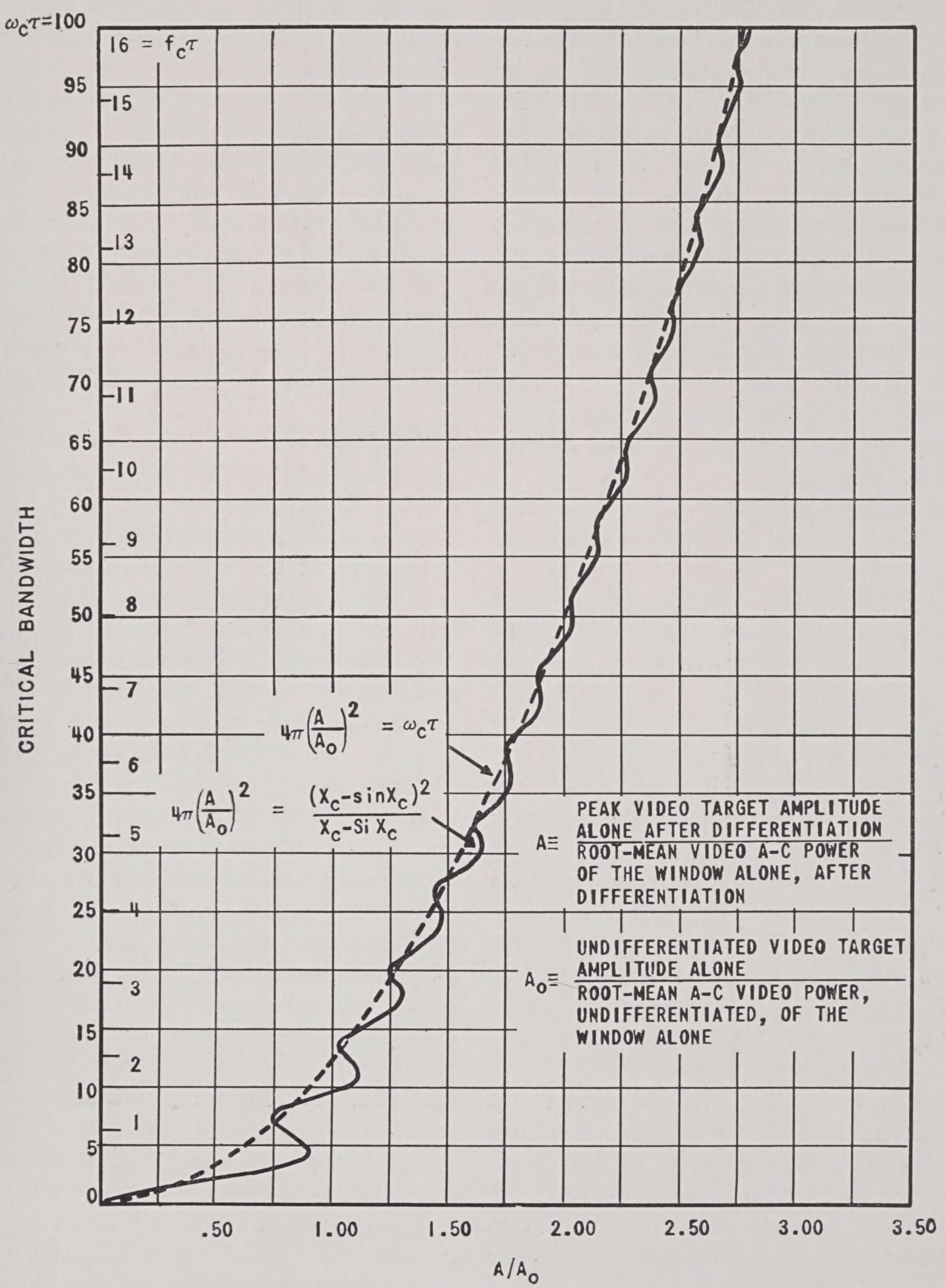


FIGURE 31. Video differentiation improvement A/A_o as a function of critical bandwidth.

the *improvement* produced by the differentiator, or analogous circuits, and is seen to be independent of the value of A required for visibility. It is independent also of the absolute value of

the analysis[330] are outlined below for the AJ system against Window discussed above. The essential requirement is wide i-f and video bandwidths. In particular, it was found that:

SECRET

1. For short-pulse systems, where the pulse length τ is of the order of 1 μsec or less, not much improvement can be obtained against Window, as the i-f and video filters cannot be spread to the necessary bandwidths. Widening as much as possible gives some improvement; but an increase, of say 25 per cent, in the amount of Window dropped, over the minimum quantity effective in jamming the unprotected set, probably destroys visibility completely.

2. For long-pulse systems, with τ equal to 3 μsec or more, considerable improvement is possible within the practical range of design values. Improved, long-pulse sets may also take more than the minimum quantity of Window and still yield visible signals. For example, a 10-μsec system may be adjusted to "read through" twice the minimum amount of Chaff effective against the unprotected system.

3. Against corner reflectors and Rope the method should be at least as effective as against Chaff.

4. The cutoff frequency f_c which must be used varies approximately as the square of the amount of Window dropped. An approximate formula for the above effect is

$$f_c\tau = 2\left(\frac{A}{A_0}\right)^2, \quad f_c\tau > 3.$$

The quantity A_0 varies inversely as the quantity of Window dispersed.

5. The frequency response of the optimum "composite" receiver filter was determined and shown to represent an improvement of about 1.41 to 1.5 in the ratio A/A_0 over this ratio for a simple RC circuit alone. This corresponds to a gain of 3.0 to 3.5 db. A circuit having the approximate frequency characteristics of the (theoretical) optimum filter was considered and also yields about 3-db improvement over the differentiator. However, because of the complexity of an optimum filter, an RC circuit may be more practical. An additional stage or two of amplification is probably necessary in either case.

6. Single differentiation, in the video amplifier, is more effective than multiple differentiation.

7. When any of these circuits is used there is a loss in range, because the i-f stages are mismatched and because thermal noise is generated in the mixer. When f_c is eight times its normal, matched value, the effective range in the absence of Window is reduced 25 per cent. As more Chaff is dropped, if the cutoff frequency is correspondingly increased, the reduction in range also increases.

8. The AJ measure is also applicable against narrow-band noise jamming, where the noise spectrum is narrower than either the *original* i-f or video bands of the receiver. The systems fail badly when the noise is wider than the bandwidth of the unadjusted i-f and video stages.

9. The method is designed for type A presentation. It is not nearly so effective in systems which have limiting, particularly sets employing a *plan-position indicator* [PPI] display.

Frequency Sensitivity of Complex Targets

A brief theoretical analysis[690] was carried out on the fluctuations of the echo from complex targets produced by small changes in the carrier frequency of the incident wave. The targets considered were those composed of two or more reflectors spaced a number of wavelengths apart. This investigation was begun in connection with the proposal to use frequency modulation of a carrier in order to distinguish large, complex targets, such as ships, from radar decoys or other similar reflectors of small physical size.

It was found that, when a radar echo is made up of the sum of a large number of separate reflections whose phases vary in a random manner relative to the transmitter, the amplitude of the resultant echo fluctuates according to the Rayleigh amplitude-distribution law. If the number of separate reflectors is small, the resultant return still obeys the Rayleigh law provided that each individual echo follows that distribution. In addition, the problem of two reflectors was dealt with, in the case where the echo amplitudes from the reflectors are equal and constant but where the relative phases vary at random.

The results of this study are shown in Figures 32 and 33. The former illustrates the probability distribution of echo amplitudes (relative to the rms amplitude) when any number of reflectors are involved, each with random phase and Rayleigh distribution of amplitude. This figure also shows the probability curve of amplitude from the two equal reflectors whose relative phase alone varies. Figure 33 shows the proba-

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bility distribution of the difference between any two amplitude measurements made at random times for the two cases described above. These latter curves are seen to be extremely similar despite the difference between the curves of Figure 32; thus, the two types of targets should behave in the same manner under frequency modulation and give equally reliable complexity indication. It was concluded, therefore, that the exact nature of the target was of little importance as long as it was complex in nature. To a large extent this conclusion was confirmed by experimental investigations.[690]

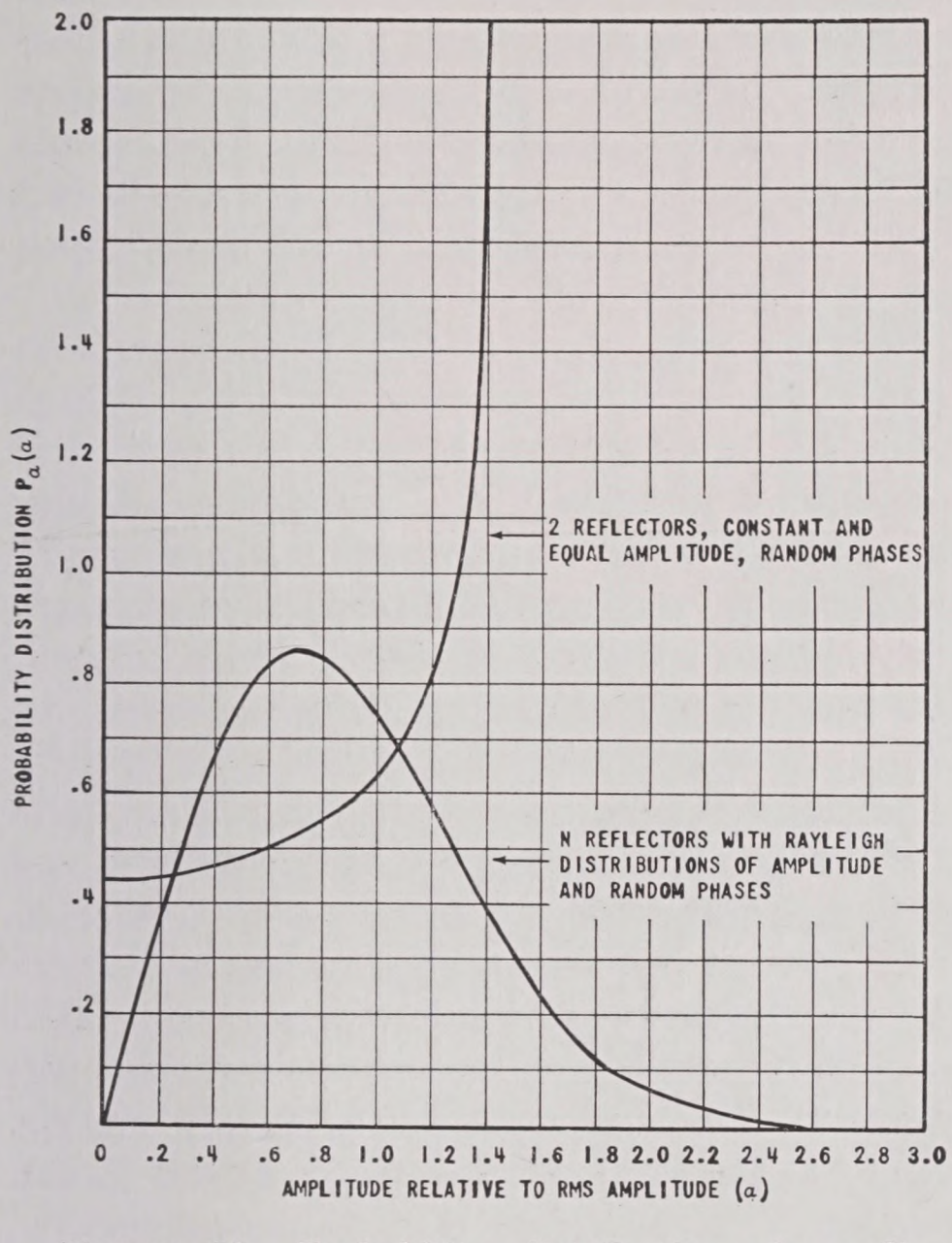


FIGURE 32. Probability distribution of amplitudes from multiple reflectors.

6.3.2 Radiation and Propagation of Radio Waves

Much of the theoretical work carried out in the course of the RCM program dealt with the radiation, propagation, and reflection of radio waves. Among such investigations were several theoretical studies of antenna problems (including those concerned with antennas for search receivers), studies of propagation problems, an analysis of the theory of radar echoes from ship targets, and studies of the radar cross sections of both airplanes and ships.

Theoretical Antenna Studies

In all RCM work, or for that matter in all radar or communication problems, antennas ultimately play a part, in both the receiving and transmitting aspects of radar and RCM problems. Theoretical studies of various kinds were undertaken to determine the radiating properties and other important characteristics of some of the antennas used in RCM.

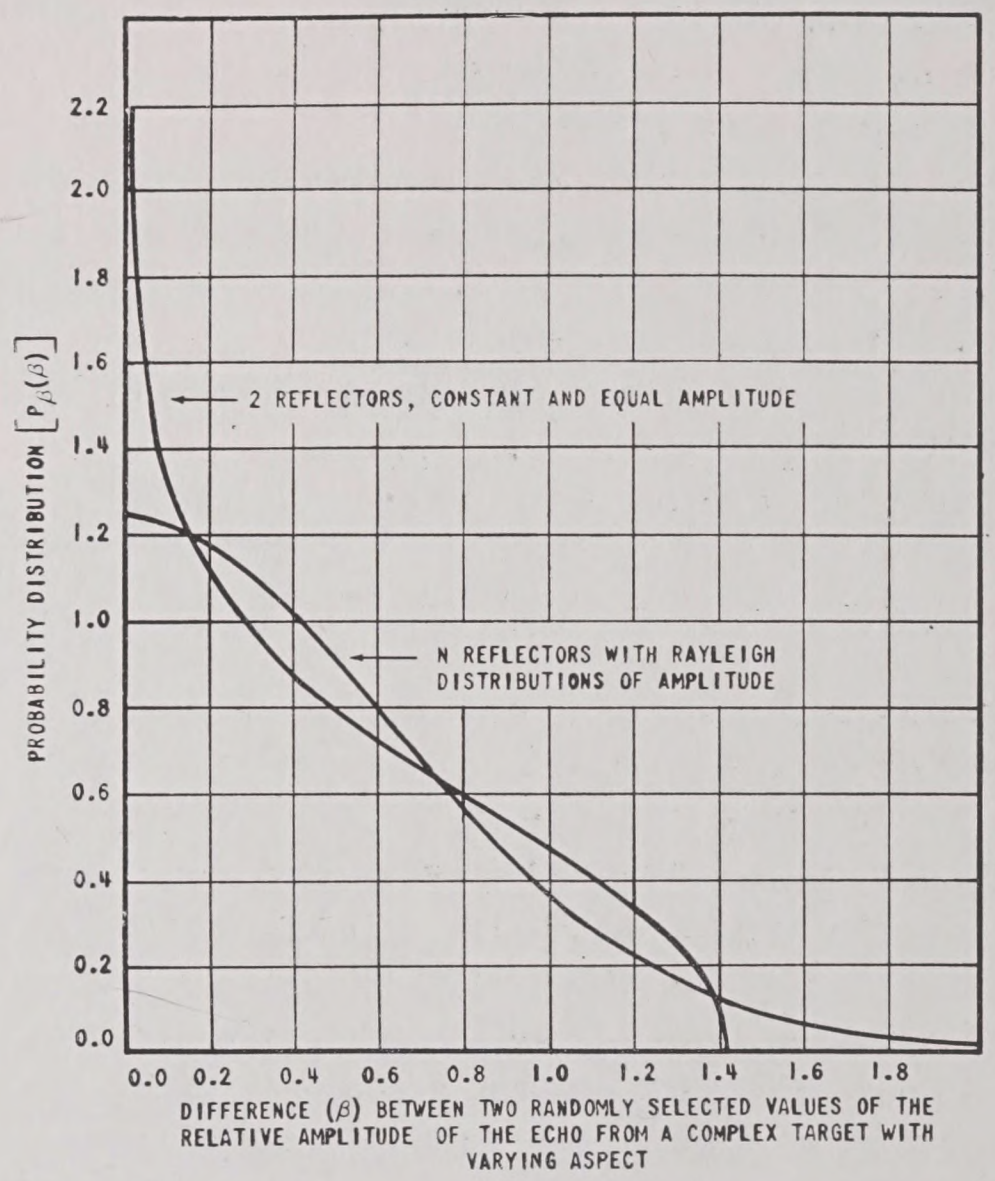


FIGURE 33. Probability distribution of amplitude differences.

General Antenna Problems. In this latter connection an investigation of the equivalent radius of thin cylindrical antennas was undertaken.[477] It was shown that, for a cylindrical antenna (or scatterer—see Section 6.3.1), whose linear cross-sectional dimensions are small compared to both the length of the cylinder and the wavelength λ, the form of the current distribution over the cross section can be determined independently

from the solution for the variation of the total current along the length. When this result is applied, for example, to the Rope problem[451] (Section 6.3.1), one finds that from any solution of the antenna problem for a thin, circular cylinder of length l, one can obtain a solution for a *flat* strip of length l and width s by replacing a, the radius of the cylinder, by $s/4$ in all formulas. Moreover, if the cross section of the cylinder is an ellipse of semimajor axis b and semiminor axis μb, then the solution of an antenna problem for the circular cylinder can be applied to the elliptic cylinder by replacing a by $\frac{b}{2}(1 + \mu)$.

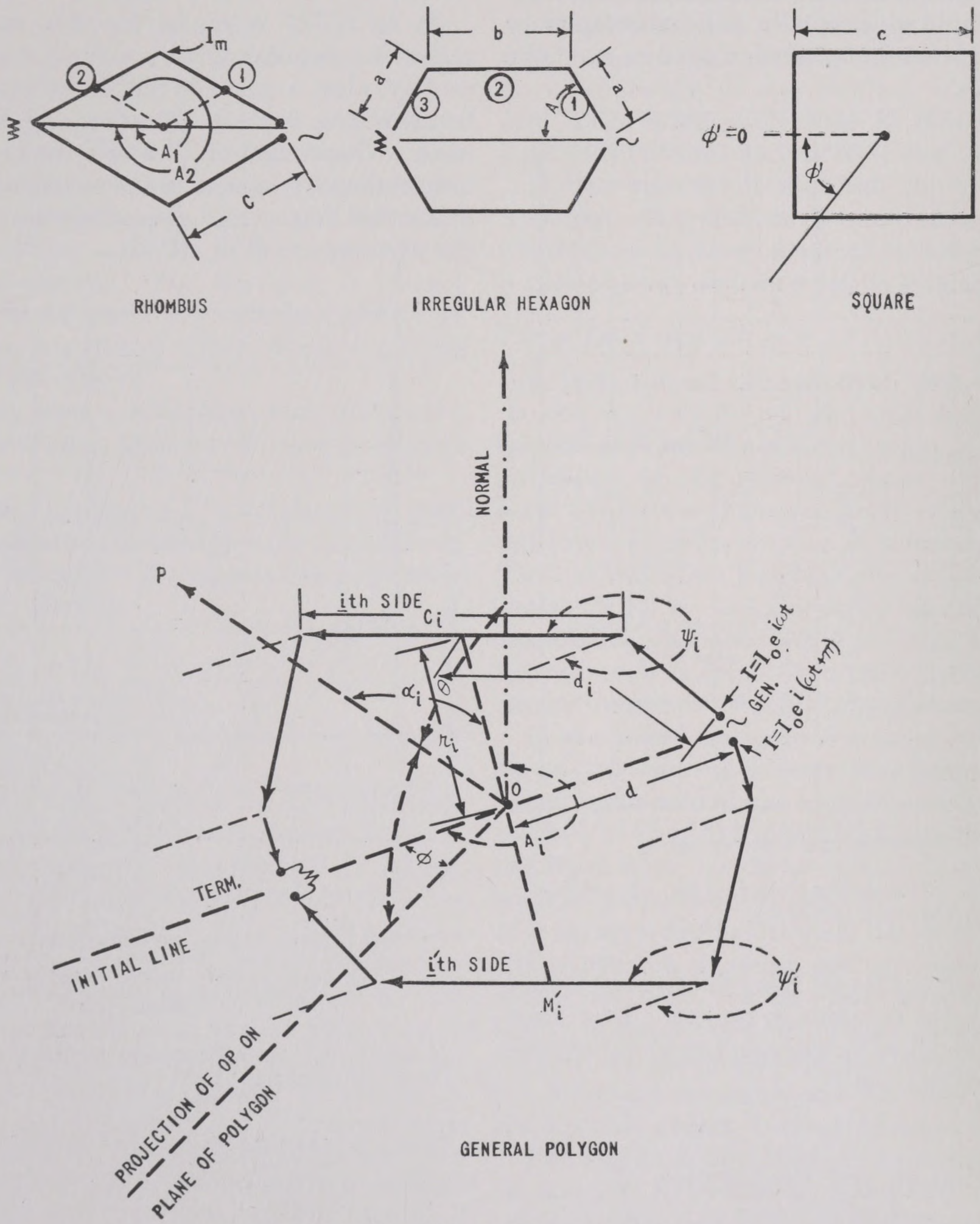


FIGURE 34. Various antenna shapes.

Another brief study was made on the "equivalent point" antenna, of constant-current epoch.[371] The idea of equivalent point antennas is inherent in the method of analysis, whose purpose was

the calculation of the Poynting flux at a remote point. A physical interpretation of such a calculation is that the infinitesimal parts of the antenna have all been translated, with appropriate changes of phase, to a chosen origin where together they constitute an infinitesimal radiator whose current moment generally depends in magnitude and phase on the direction from which it is viewed. While it was previously recognized that the origin could be chosen anywhere near the antenna, there was an impression that some unique point exists which may be regarded as a kind of centroid of the radiating current elements, and there was speculation about whether such points exist for all antennas.

A criterion whereby the existence of such preferred points may be recognized was found—namely, that the most desirable choice of origin is that for which the current phase of the equivalent point radiator is independent of direction. These points, however, do not always exist. For example, in the case of the quarter-wave resonant section, such a point cannot be found. It is sometimes possible, by replacing finite segments with equivalent points (when they are specifiable), to simplify the reasoning and computation whereby the properties of the whole antenna are obtained. The greatest simplification is achieved when the current moments of the equivalent points of all segments are directed along the same line and are equal in magnitude and phase. Specific calculations were carried out for a number of simple, illustrative examples.[371]

Loop Antennas. An examination of means for determining the radiation characteristic of antennas in the form of large polygonal loops was also considered.[475] The following definitions are helpful in stating the principal result:

λ = wavelength in air;
$\beta = 2\pi/\lambda$;
r = distance from equivalent point source;
θ = polar distance measured from normal to loop;
ϕ = longitude measured from an arbitrary line;
I_0 = amplitude of the current;
I = complex current;
$d\Omega$ = element of solid angle;
E = complex electric intensity (distant field);
H = complex magnetic intensity (distant field);
F = equivalent current moment;
Φ = mean power radiated per unit solid angle;
R = radiation resistance;
d = directivity defined as $\Phi/\Phi_{\text{space averaged}}$.

$$E_\theta = \frac{-30i\beta e^{-i\beta r} F_\theta}{r}; \qquad E_\phi = \frac{-30i\beta e^{-i\beta r} F_\phi}{r} \tag{102a}$$

$$H_\theta = \frac{i\beta e^{-i\beta r} F_\phi}{4\pi r}; \qquad H_\phi = \frac{-i\beta e^{-i\beta r} F_\theta}{4\pi r}. \tag{102b}$$

$$\Phi = \frac{15\pi}{\lambda^2}(F_\theta F_\theta^* + F_\phi F_\phi^*); \qquad R = \frac{2\int \Phi d\Omega}{I_0^2}; \qquad d = \frac{4\pi\Phi}{\int \Phi d\Omega}. \tag{102c}$$

The general antenna is shown in Figure 34. For the whole polygon the components of the equivalent current moments are

$$F_\theta = 2iI_m \cos\theta \sum_{i=1}^{n} c_i \frac{\sin u_i}{u_i} \cdot \sin\left[\beta_0 r_i \cos\alpha_i + \beta_1\left(\frac{\sigma}{2} - d_i\right)\right] \cos(\alpha_i - \phi), \tag{103a}$$

$$F_\phi = 2iI_m \sum_{i=1}^{n} c_i \frac{\sin u_i}{u_i} \cdot \sin\left[\beta_0 r_i \cos\alpha_i + \beta_1\left(\frac{\sigma}{2} - d_i\right)\right] \sin(\alpha_i - \phi), \tag{103b}$$

where I_m refers to the current measured in the middle of the chain of n sides, and σ is the sum of the lengths of the n sides. Here d_i is the distance along the wire from the generator to the middle of the ith side, r_i is the radius to the middle point of the ith side, and α_i is the angle between this vector and the direction of the field point. The quantities u_i are given by $c_i/2$ $(\beta_1 - \beta_0 \cos \psi_i)$, where now ψ_i is the angle between the direction of the ith side and that of the field point, and c_i is the length of side i. The subscript "0" is used for waves in air and "1" for waves along the wire.

The general expression, equations (103), take different and generally simpler forms in a number of important special cases.[1] For a *circle* with a

[1] The regular polygon with traveling waves or with a uniform current distribution is not considered here; the reader is referred to page 6 of reference 475.

SECRET

uniform current and radius a we have

$$F_\phi = 2\pi i I a J_1 (\beta_0 a \sin\theta),$$
$$F_\theta = 0, \tag{104a}$$

and ($\beta_0 = \beta$) here,

$$\Phi = 15\pi I_0^2 \beta^2 a^2 J_1^2 (\beta a \sin\theta);$$
$$d = \frac{2J_1^2 (\beta a \sin\theta)\ \beta a}{\int_0^{2\beta a} J_2 (y)\, dy}; \tag{104b}$$
$$R = 60\pi^2\ \beta a \int_0^{2\beta a} J_2 (y)\, dy,$$

where J_1 is the familiar Bessel function of the first kind, first order. For the radiation resistance in this case, see Figure 35. Calculations showed that at moderate frequencies polygons with uniform current have nearly the same properties as circles.

For the *square* with uniform current the following results were obtained:

$$F_\theta = 0;$$
$$F_\phi = iI\beta c^2 \sin\theta \frac{\sin u_1}{u_1} \cdot \frac{\sin u_2}{u_2}, \tag{105a}$$
$$\Phi = \frac{15}{4\pi} (\beta c)^4 I_0^2 \sin^2\theta \left(\frac{\sin u_1}{u_1} \cdot \frac{\sin u_2}{u_2} \right), \tag{105b}$$

where $u_1 = \frac{1}{2}\beta c \sin\theta \sin(\phi - \pi/4)$ and $u_2 = \frac{1}{2}\beta c \sin\theta \cos(\phi - \pi/4)$; here c is the length of a side, as before.

For a *rhombus* with traveling waves it was found that

$$F_\theta = -2iI_m \beta c^2 \cos\theta \sin\phi \sin A \frac{\sin u_1}{u_1} \cdot \frac{\sin u_2}{u_2}, \tag{106a}$$
$$F_\phi = -2iI_m \beta c^2 \sin A (\cos\phi - \sin\theta \cos A) \cdot \frac{\sin u_1}{u_1} \cdot \frac{\sin u_2}{u_2}, \tag{106b}$$
$$\Phi = \frac{60}{\pi} \beta^2 c^2 I_0^2 \sin^2 A \frac{\sin^2 u_1}{u_1^2} \cdot \frac{\sin^2 u_2}{u_2^2}, \tag{106c}$$

where now $u_1 = \frac{1}{2}\beta c [1 - \sin\theta \cos(A + \phi)]$ and $u_2 = \frac{1}{2}\beta c [1 - \sin\theta \cos(A - \phi)]$, and A is the longitude of the first side. The formulas for F do not appear to have been given previously in a concise form. Other possibilities were considered, such as the irregular hexagon with traveling waves, and with symmetry with respect to rectangular axes, one of which is the initial line $\phi = 0$. Loops with standing waves and the problem of driving large loops with uniform current were also examined, as well as possible applications of these various antennas to problems of direction finding.[475]

Search Receiver Antennas. Much of the theoretical work on antennas was concerned with the search receiver problem, of which the optimum conditions for finding and observing enemy signals (primarily radar) is the principal question.

One study dealt with the use of continuously rotating direction finders against signals of varying intensity.[661] When such direction finders, having azimuthal scope presentation, are used to locate rotating beam transmitters, the variation of the field strength at the receiver causes each curve drawn on the scope to indicate a false direction. There appeared to be two ways to overcome the difficulty: (1) If the receiving antenna is rotated at such high speed that a considerable number of curves are drawn on the scope for one turn of the transmitter, the largest curve of the group of curves gives a good indication of the desired direction. There are a limited number of slow-speed ranges which give as good a result, but these lack the advantages of persistence on the screen. (2) If two direction-finding antennas, whose directivity diagrams are mirror images of each other, are caused to rotate at equal speeds in opposite directions, they may be adjusted in relative angle so that their outputs cause identical curves to be traced on the scope. The true direction then bisects the angle between the two indicated false directions. Apparatus which cannot be run at high speed should be run either at nearly one-to-one, or else so slowly that the required number of curves are drawn during one turn of the receiver antenna. In the latter case, a group of curves closely resembles a set of radial lines equally spaced in angle.

A further study was carried out on the optimum directivity pattern for search antennas.[693] Because airborne search antennas must be small, the area within which radar transmitters may be detected is correspondingly limited. The search airplane is accompanied in flight by a closed curve which has the property that, if a certain radar is within it, the signal can always be observed, provided the receiver is "illuminated" and properly tuned. The radius of this antenna curve is proportional to the square root of the power directivity of the receiving antenna. In order to scout as rapidly as possible, it is desirable to have the antenna curve extend sidewise as far as the horizon permits. Requirements for direction finding are better satisfied if the antenna

[redacted]

curves slant forward to some extent. The amount of sidewise gain that can be used is limited by the fact that increased gain implies a shorter interval of time which the radar spends within the curve. This time interval determines the chance of a concurrence of illumination by the radar and proper tuning of the receiver. Supposing that a minimum acceptable probability of detection has been chosen, it is found that the fore-and-aft distance across the antenna curve should be uniform and not less than that which corresponds to the acceptable probability.

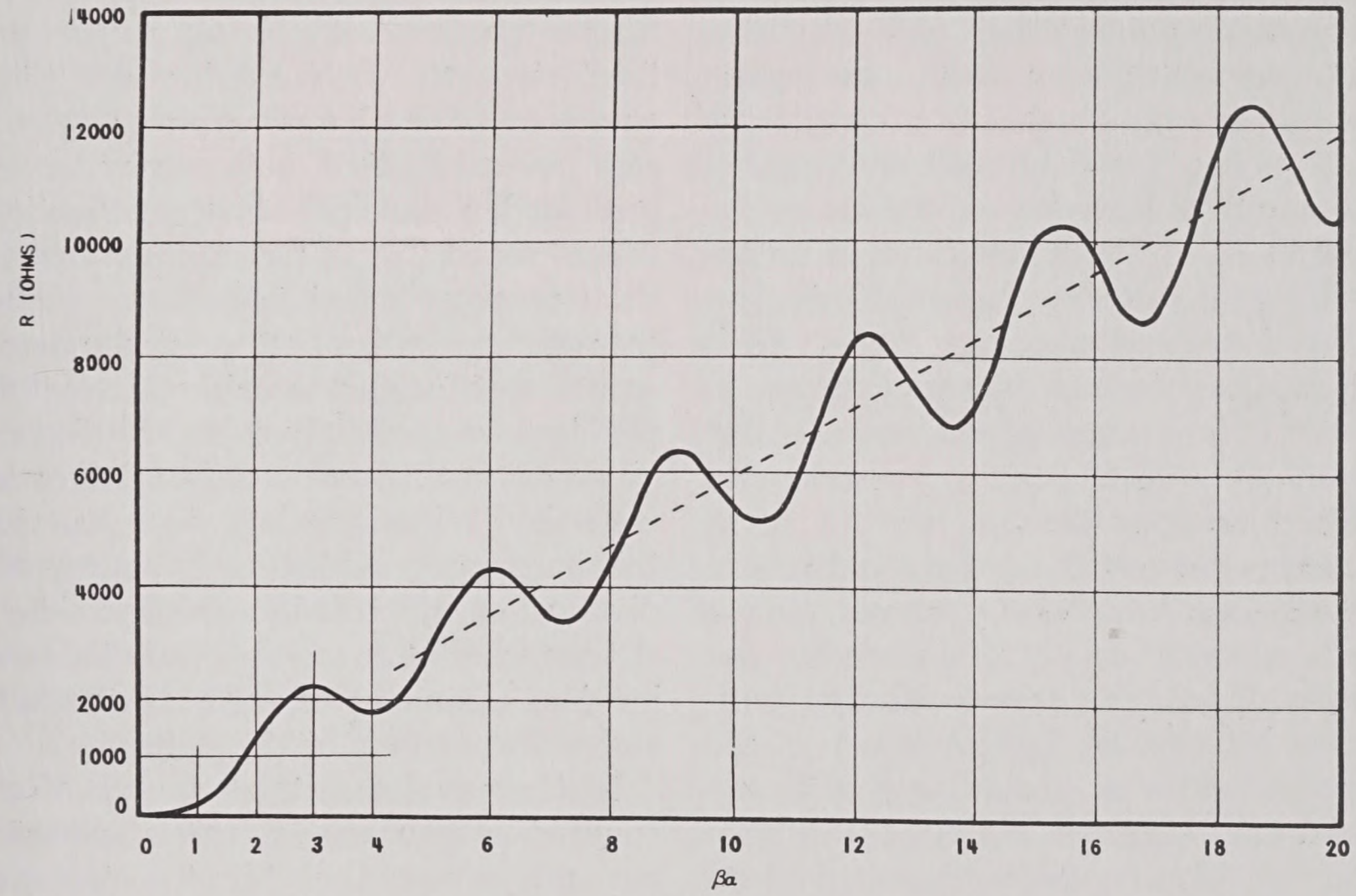


FIGURE 35. Radiation resistance, circular loop antenna as function of radius.

In order to detect radars which lie nearly in the track of the search plane there should also be a forward lobe extending beyond the distance at which the enemy operator will probably shut off his radar. The extent of this lobe also depends on the probability involved.

PROPAGATION STUDIES

In developing a jamming system or in solving a specific jamming problem, a knowledge of the propagation of radio waves is essential, in order to estimate the field intensity which the enemy is delivering to his receiver and then to determine the power or distance required to lay down a field sufficient to jam reception. Jamming is almost invariably done by means of ground-wave transmission, since ionospheric conditions limit the frequencies which can be used for sky-wave transmission over a given jamming distance to such an extent that sky-wave jamming is generally unprofitable. The propagation information gathered was therefore confined to ground waves.

The variation of ground-wave field intensity with distance depends on several factors, among which are frequency, polarization, antenna elevations, and type of terrain—that is, whether the radio path is over sea or land and whether the land is flat or mountainous, jungle or relatively open. Although a considerable amount of information had been published on radio propagation, the need to organize this material in a more usable form for rapid reference was recognized early in the RCM program. The most recent compilation of such information is Issue 3 of the handbook *Propagation Curves*,[193] compiled by the Bell Telephone Laboratories, Inc. (under contract OEMsr-966). This handbook supersedes similar information previously given in

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earlier reports[59, 192, 218] and handbooks.[187] Another study of ground-wave propagation[83] was carried out by the Radio Corporation of America (under contract OEMsr-895).

The material in the latest handbook[193] is in the form of curves which can be used to estimate the received field intensity of ground-wave signals when they are being transmitted (1) between an aircraft and a ground station, (2) from one aircraft to another, and (3) from one ground station to another ground station, at frequencies from 200 kc to 600 mc. The information covers air-plan elevations as high as 40,000 ft and distances up to 500 (statute) miles, for both horizontal and vertical polarization and for three types of ground conditions: namely, sea water, good soil, and poor soil. In addition to revisions of the earlier curves, the handbook contains an explanatory text, and includes curves for evaluating the effects of antenna elevation, a nomogram for estimating "shadow losses" caused by hills, and a brief statement on tree losses. This handbook provides reference material of use in estimating not only jamming performance but radio communication performance as well, and therefore has wide application.

These curves served to illustrate the tremendous advantage of an airborne jammer over a ground-based jammer, brought about by the higher antenna elevation. Since airborne jammers can also be carried much closer to the target, more effort was accordingly directed toward developing airborne jamming than toward similar developments for ground-based jamming. Future work on wave propagation involves consideration of higher frequencies which may come into more common usage and augmentation of the present data (which are based on the assumption of standard propagation conditions) with whatever information becomes available on the effects of special conditions in the lower atmosphere.

Analysis of Ship Echoes

The foregoing propagation studies (as well as others) were of considerable use in an analysis[592] of the echoes from ships and other naval targets. This study was concerned with the formulation of a theory to permit the approximate calculation of the power density of radar echoes returned from naval targets and the computation of jamming powers and minimum jamming distances in naval operations. For normal propagation conditions, formulas were developed to permit such computation at distances within the radar horizon. The conditions for maximum effectiveness of a given jammer were analyzed and the practicability of various available jammers was evaluated.

Parameters and Formulas. The estimation of radar echoes from ship targets is essentially more difficult than the parallel problem for aircraft. The difference is accounted for by three factors: (1) reflection from the sea, which produces interference patterns exhibiting a rapid variation of field strength with height; (2) the increased extension of the target, which allows it to intercept several lobes of a nearby radar; and (3) the increased complexity of the reflecting surfaces, which results in a larger fluctuation in return than is experienced with an airplane. In the case of the airplane, although the dependence on aspect and frequency cannot be eliminated, the problem was partially solved by the introduction of an effective cross section, determined experimentally. This method was practical because the parameter as defined is independent of the distance at which it is measured—a consequence of the fact that at any distance the power density incident upon the airplane is essentially constant across the surface of the target.

In the naval case the presence of an extended conducting surface, the sea, causes the field strength across the ship to vary rapidly with height. This new element in the problem makes it necessary to distinguish two zones, in order to reduce as much as possible the variation of the reflection parameter with distance. In the first of these regions, the one closest to the radar installation, the echo power density is given in terms of an effective cross section whose dimensions are length squared, as in the case of an airplane; because of this similarity, the region was called the "Air-zone." At larger distances, the ship was said to be in the "Sea-zone." In this region, the echo power density is attenuated as the eighth power of the radar-to-target separation, and the echo parameter used is a constant whose dimensions are length to the sixth power. This region was the one most commonly encountered in operations involving the jammers

available during World War II. In the Sea-zone, the echo power density displays a very strong dependence upon the height of the radar antenna and upon the frequency; this dependence is not observed in the Air-zone.

All the foregoing was derived on the assumption of a plane, perfectly conducting earth, and a normal atmosphere. The plane earth assumption is sufficiently accurate in distances up to two-thirds of the radar horizon (or perhaps farther), whereas the assumption of a perfect conductor is applicable to sea water in the most practical case of horizontal polarization. At larger distances, it is necessary to consider a third zone, in which the curvature of the earth and ultimately the diffracted ray play a part. In this region, a general solution to the problem becomes almost impossibly complex, but an approximate solution was derived which extended the useful range of the analysis as far as the radar horizon, with reasonable accuracy.

Formulas were derived[592] for the echo power density, the minimum screening range for a jammer of known power, and the power required to jam to a given range. When the target is well into the Sea-zone, the minimum jamming distance is proportional to the fourth root of the ratio of the effective radar power to the effective jammer power; to the square root of the ratio of radar antenna height to jammer antenna height; to the square root of the frequency; and to the fourth root of the Sea-zone reflection parameter. In the Air-zone the dependence of the minimum jamming distance on radar and jammer parameters is more complicated, but under most conditions the proportionality is roughly the square of that listed for the Sea-zone case.

Under many conditions, the solution for the minimum jamming distance could not be written explicitly; but graphical solutions were devised and curves were drawn to permit the rapid calculation of the minimum range.

Operational Considerations. On the basis of the equations discussed above, the minimum jamming distance was calculated for a variety of operational situations with the jammer on the target vessel. Such calculations were performed for a wide range of ship sizes, for several frequencies, and for both low-power and high-power jammers. Although the computations were carried out for the purpose of illustrating the techniques of calculation developed, the results shed considerable light upon the usefulness of various types of jammers.

Consideration was given to the question of screening a ship with a jammer carried on an airplane. It was concluded that, if a given jammer and antenna are installed on an aircraft, their effectiveness in screening a ship is at least as great as the effectiveness of the same jammer and antenna carried on the ship itself, and often greater—provided that the most effective use is made of the jammer in both arrangements. (In some cases, especially in small ranges, it is impracticable to use an airborne jammer in the most effective way.) On the other hand, it is frequently possible to carry a much larger jammer and a much higher-gain antenna on a ship than on aircraft.

A short study was made of the use of Chaff or other forms of Window to simulate or screen surface vessels. It was concluded that, except at very great ranges or for very small ships, the amount of Chaff required for these purposes made its use impracticable.[592]

Equations were derived for the optimum height of the jammer antenna, both for "off-target" jamming (when the jammer is not carried on the target vessel) and for the self-screening case (when it is). These formulas showed that, although it is generally desirable to place a jamming antenna as high as possible on a ship, this is not always the case. For really powerful jammers, the exact height of the antenna may be of considerable importance. With low-power jammers, however, the minimum jamming distance is almost always in the Sea-zone; and in this case the higher the antenna, the more effective is the jamming.

Derivation of Equations. Two different derivations were carried out for the basic equations of the analysis. The first employed a number of simplifying assumptions in an attempt to show briefly the physical reasons for the results gained. The equations were also derived in as rigorous a way as was possible; although this derivation is far from exact, the theory is in such a form that any errors are minimized. The "rigorous" derivation showed that the results of the simpler one were somewhat more accurate than one might conclude from the simplicity of the assumptions used.[592]

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Analysis of Radar Cross Sections

In order to perform the actual computation of minimum jamming distances and other quantities of interest, experimental figures on the reflection parameters (radar cross sections) were required. It was found that the raw experimental data could not be used directly but had to be studied and averaged in order to be of use.

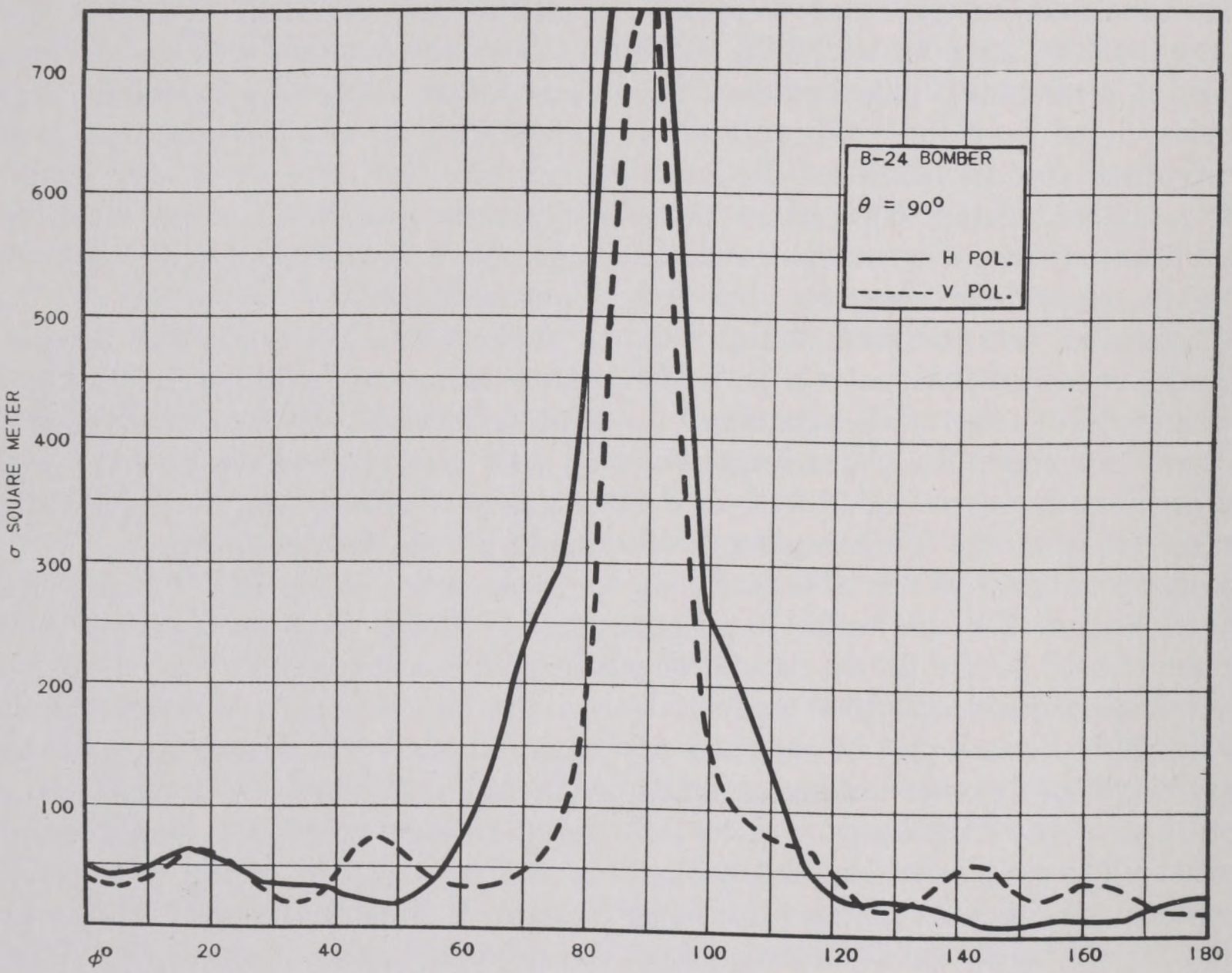


FIGURE 36. Average radar cross section per aircraft in formation, horizontal aspect.

Ship Cross Sections. A very large amount of experimental data on radar reflections from ships was analyzed, in connection with the study of ship echoes, and values of the Sea-zone and Air-zone reflection parameters were thus calculated for a variety of different ships. The results of these calculations were tabulated, and revisions were made as additional data became available.[592]

It was thought desirable to list parameters which would be widely applicable over a class of ships and a variety of frequencies and still not be cumbersome. For this reason, and because of the uncertainty as to the precise accuracy and generalized validity of the data, the tables were compiled by averaging the parameters over all frequencies. It was felt that the wide scattering of the original figures provided sufficient weighting to the abnormally large values of the parameters so that the averages tabulated were amply conservative—too large rather than too small.

As further data became available in reasonable quantities, the same procedure was followed. On the basis of these additional results, the original figures were revised. (It was generally found that the original values were too large.) The revised tables were turned over to the Navy but were never published or distributed generally.

Airplane Cross Sections. Measurements were made by the Ohio State University Research Foundation of the radar cross sections of aircraft; the experiments were performed on scale models of the airplanes for a variety of frequencies (see Section 6.5). These data were analyzed and averaged, so that they could be applied to operational problems.[659, 660]

The complicated lobe structure of the reflection patterns from the airplanes, as measured experi-

SECRET

mentally, indicated that some procedure for smoothing the data would be required before they could be put to practical use. Methods were developed for this purpose, as well as for using the results in various operational applications. The dependence of the airplane cross sections on polarization and frequency was investigated. It was found that measurements on vertical and horizontal polarizations alone were insufficient to enable the prediction of the response on intermediate polarizations. It was noted also that the smoothing procedure used increases in validity with increasing frequency.

The averaging process was carried out, and the results plotted and tabulated, for all the various measurements available from Ohio State University. Figures 36 and 37 show typical curves resulting from the analysis.

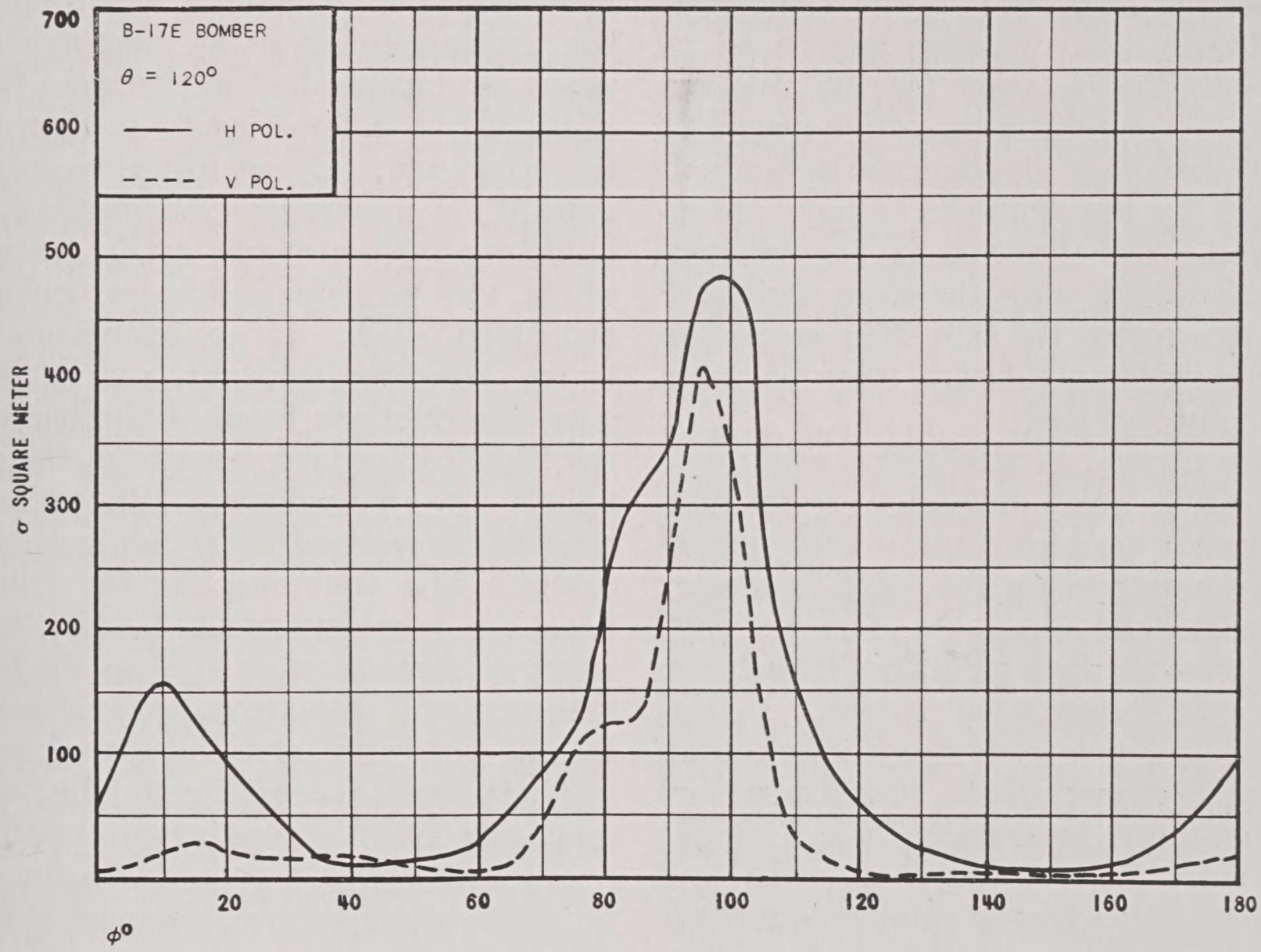


FIGURE 37. Average radar cross section per aircraft in formation, from below.

6.3.3 Transmission Lines and Wave Guides

The properties of transmission lines and wave guides received a considerable amount of theoretical attention. Some of the theoretical studies dealt with the properties of lines and guides as used for the transmission of r-f energy; the large majority of the investigations, however, were concerned with various applications of the impedance-transforming properties possessed by sections of transmission line.

Such sections of line were used, singly or in combination, in a variety of ways: as resonant systems or component parts thereof, as transformers to match impedances, or in the construction of filters. In considering these applications of line sections, it should be remembered that the equations for the impedance looking into a section of the transmission line are the same as those for a section of wave guide. A great many of the theoretical results summarized in the following paragraphs, therefore, could be applied equally well to sections of wave guide, even though they were derived originally for transmission lines.

Properties of Lines and Guides

As stated above, several studies were made of the general properties of transmission lines and wave guides. One of these dealt with the char-

SECRET

acteristic impedance of a shielded, balanced transmission line, composed of two inner conductors symmetrically placed within a cylindrical shield.[482] A comparison was made between three formulas for this characteristic impedance, and expressions were derived for the errors in them. The formulas were taken from various sources, two of them from the German literature.

Velocity of Propagation in Coaxial Line. A theoretical investigation was made of the group velocity of electromagnetic waves in a coaxial line. If there is resistance in the conductors composing the line, a correction term must be introduced into the equation for the velocity. The usual expression for this correction term does not include the result of the change in self-inductance produced by the skin effect which accompanies the resistance. Expressions for the complete correction term were therefore derived,[377] and it was shown that the skin effect correction is normally considerably larger than the term which is usually included.

Ridge Wave Guide. A study was made of a rectangular wave guide having a rectangular ridge projecting inward from one or both sides.[709] Equations were derived for the cutoff frequency and the characteristic impedance of such a wave guide, and curves for these quantities were drawn for the various transmission modes. It was shown that ridge wave guide has a lower cutoff frequency and characteristic impedance and greater higher-mode separation than a simple rectangular wave guide of the same width and height. The equation for the cutoff frequency is fairly accurate for any practical cross section. The impedance equation is strictly accurate only for an extremely thin cross section. Values calculated by the use of this equation, however, were found to check experimental values very closely. A variety of different applications for such a guide were investigated.[687, 719, 727]

Resonant Circuits and Systems

A number of studies were carried out on the general properties of resonant systems and of sections of transmission lines used as resonant circuits, as well as applications of such systems. As suggested previously, the results for line sections could be applied to wave guides also.

Analysis of Resonant Systems. An analysis was made of resonant systems for ultrahigh frequency from the point of view of external impedance measurements.[663] Resonant systems in the form of four-terminal networks are mainly used as band-pass filters and impedance-matching transformers. In a tank circuit of a vacuum-tube oscillator or amplifier, these functions are combined, and the analysis was performed with this application in mind (although its scope can easily be extended).

Most of the resonant systems used at ultrahigh frequency have more than one resonant mode, and each mode of a four-terminal system has a complete set of at least five parameters which are independent in the sense that none of them can be determined from known values of the other four. Direct measurements are often difficult or impossible—for instance, in distributed-constant systems or in vacuum tubes where the resonant system is enclosed in the evacuated shell. If an equivalent circuit in terms of lumped constants can be found, however, the relations between the parameters and the "cold" impedance seen from the output terminals are easily derived; the parameters can then be determined by standing-wave measurements. The equations for the calculation of approximately equivalent circuits for common resonant systems were studied on the basis of accuracy and simplicity of analysis. Experimental procedure and sources of error in impedance measurements by standing-wave determinations were investigated briefly, and a number of methods were set up for calculating the parameters of the resonant systems from standing-wave data, with the aid of graphs and simple formulas.

Resonant-Line Sections. If a section of transmission line is short-circuited at one end and terminated at the other end in a reactance, a load resistance, and a power source, the section will resonate with the terminating reactance; and such an arrangement is often used as a resonant circuit at high frequencies. If the terminating impedance and source are in series across the end of the section it acts as a series resonant circuit, whereas if these elements are in parallel across the section it behaves like a parallel resonant circuit.

Equations were derived for the frequency bandwidth of such a resonant section for both series and parallel resonance.[437] Two special

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cases were considered: (1) the loaded section, where the load resistance is of such a size that it receives almost all the power; and (2) the unloaded section, where the size of the load resistance is such that all but a negligible fraction of the power is delivered to the section. The form of the equations is such that they apply to either an inductive or capacitive termination.

The condition for resonance was found: namely, that the reactance looking into the shorted section without the termination be equal and opposite to the terminating reactance. It was shown that there was a series of values for the angular length of the line which satisfy this resonance condition; these values are known as the modes of resonance. Equations were derived giving the change in frequency band produced by a shift in the mode of resonance, for all the cases mentioned above—that is, series and parallel resonance, and loaded and unloaded sections. Since the angular length of the section is proportional to the product of its physical length and the frequency, the mode of resonance may be shifted by changing either the length of the frequency; both methods of shifting modes were considered.[437]

Mode Separation in an Oscillator. A common type of h-f oscillator uses two sections of coaxial transmission line as resonant circuits, of the type discussed above. One of these sections maybe considered to determine the frequency of oscillation in accordance with the resonance condition and, of course, a number of different modes are possible. The adjustment of the other section may then be considered to determine at which of these possible frequencies the apparatus actually oscillates. The difference in the physical lengths of the second section for the two modes under consideration is known as the *mode separation*, and it is important that this separation be as large as possible to prevent the oscillator from producing more than one frequency.

The problem of separating the first and third modes of oscillation in a coaxial oscillator of this type was considered.[484] The equations involved could not be solved directly, but a comparatively simple graphical solution was found. It was shown that the mode separation increases with the difference between the product of the terminating capacity and the characteristic impedance for the two sections. In addition, it was concluded that the mode separation varies quite slowly as a function of resonant frequency.

Design of Matching Transformers

An extensive investigation was carried out on the design and performance of matching transformers designed to cover wide frequency bands and composed of sections of transmission lines (or wave guide). The early work was concerned chiefly with a study of the behavior of matching sections of known types over a wide range of frequencies. The later work dealt largely with methods of choosing the combination of sections in the transformer and the values of the section parameters in such a way that the characteristics of the transformer would compensate for any mismatching in the load over the frequency range to be covered.

Performance of Matching Sections. Methods were found for determining the frequency characteristics of various specific types of matching transformers made of sections of line in series.[519] Equations were derived and diagrams drawn for a single quarter-wave section and for a pair of such sections. It was shown, for instance, that a quarter-wave section matching a constant resistance load has a frequency band considerably wider than is generally realized, and that two paired quarter-wave sections give an even wider band. The use of a relatively new section for matching the load at two frequencies was analyzed, as well as the tuned-circuit equivalents of this section.

Ideal Load. At this stage, the concept of "ideal" or "matching" load was introduced.[519] The ideal load is defined for a particular section or transformer as that load which, applied at one end of the section, maintains perfect matching at the other end at any frequency; in other words, the ideal load for a section at one pair of terminals is the conjugate of the load looking in the direction of the opposite pair, when the impedance to which the load is to be matched is connected at this second pair of terminals.

This concept was found to be of the greatest assistance. Once the ideal load has been calculated for a large variety of types of transformers, a matching transformer can be designed simply by choosing the one whose ideal load is most similar to the actual load to be matched. Such calculations were performed in great detail

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for a matching transformer composed of a single section of line, and charts were drawn from which it is possible to determine by inspection the frequency limits of a given load and single-section transformer (assuming a limit of 17 per cent on the reflection coefficient). A simple formula for finding the complete frequency characteristics in terms of the ideal load was also derived:[519]

$$|K|^2 = \frac{(R - R_m)^2 + (X - X_m)^2}{(R + R_m)^2 + (X - X_m)^2}. \quad (107)$$

Here $R + jX$ is the actual load, $R_m + jX_m$ the ideal load, and $|K|$ the modulus of the reflection coefficient.

Series of Quarter- and Half-Wave Sections. For all except the simplest types of matching transformers composed of sections of transmission lines, the expression for the ideal load becomes too complicated to be handled analytically (the same is true for other methods of approach to the matching problem). In order to have available a reasonable number of transformer parameters whose values could be adjusted suitably, the idea was suggested of using a series of line sections of equal length. Upon further investigation, it was found that, for more than two sections, even this arrangement could be handled only when the lengths of the sections were close to a quarter or a half wavelength.

In this case, however, the expressions, although complicated, could be handled algebraically. Equations were derived, therefore, for the ideal load of such a series of sections, and the arrangement was found to be an extremely powerful tool. Instead of writing the expressions for the ideal load as a function of frequency in the region where the sections were quarter-wave or half-wave long, the equations were written in terms of the ideal load and its derivatives at the central (resonant) frequency. In this form the equations were found to be somewhat more flexible in their application.

It was possible to write expressions for all transformers where the number of sections was not greater than four. In some cases, however, the equation could not be solved explicitly for the parameters of the transformer—that is, for the characteristic impedances of the sections. Graphical solutions were therefore constructed for transformers of this type.

Many other approaches to the general problem of designing matching transformers were investigated, and several other possible combinations of sections were considered, but the foregoing method appeared to be the most fruitful and therefore received the greatest attention.

Synthesis of Matching Sections. The problem of synthesizing broad-band matching transformers also received a certain amount of attention[93, 111] at the Radio Corporation of America (under contract OEMsr-895). Consideration was given to the problem of choosing a single section of line in such a way as to match an arbitrary load over the widest possible range of frequencies,[93] and design charts were constructed for the synthesis of some simple two-element broad-band matching transformers.[111] In general, the approach used was similar to that just described.

Wide-Band Balancing Transformer. On the basis of the work discussed above, the frequency characteristics of a particular type of balun (a transformer from an unbalanced to a balanced line) was investigated. It was found that by designing the balun properly and by inserting a properly designed pair of quarter-wave sections to match the balun to a balanced line of higher characteristic impedance, the standing-wave ratio could be kept below 1.25 over frequency bands of the order of four to one. Combination matching and balancing transformers of this type were designed and the values of the parameters calculated for the transformation from a 50-ohm unbalanced line to a 128-ohm and a 150-ohm balanced line.

Broad-band Wave Guide-to-Line Junction. In the design of microwave filters and receiver transmission systems, there was required a junction between a wave guide and a coaxial line which would operate over a frequency bandwidth greater than 2:1 with a voltage standing-wave ratio of less than 2. Several types of junctions satisfying these requirements were designed, using simple transmission line theory.[687] Some of these employed ridge wave guide of the type described previously.[709] The best of the simple junctions investigated and analyzed was found to have a bandwidth ratio of 2.7:1.

Studies of Filters

It has long been known that certain lumped-constant four-terminal networks possess useful

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filter characteristics. As frequencies are increased, however, lumped constants (first inductances, then capacitances) become increasingly difficult to realize physically. A fairly complete investigation was therefore undertaken to extend these filter concepts to circuits including sections of transmission lines, for use at ultrahigh frequency. The basic method of analysis and the resulting design-equation methods are discussed in the accompanying monograph,[809] and the summary given is therefore very brief.

Filters Using Short Sections. Short sections of transmission line (less than a quarter-wave in length) which are terminated in an open circuit or a short circuit are electrically very nearly equivalent to lumped constants. A short-circuited section less than an eighth of a wavelength long is particularly useful, and behaves like a lumped inductance. Thus, one can design many lumped-constant filters so that the coil can be replaced by line sections. Design equations and methods were derived for several filters and transformers using this method of construction.[524] Types of filters considered included one low-pass, one high-pass, and several band-pass filters. The theoretical results agreed fairly closely with experimental curves. The design equations were later extended to an improved low-pass filter of similar type.[666] This latter filter was easily constructed and could be built of wave guide as well as coaxial line, to operate in the microwave region; it consisted of short lengths of alternately high- and low-impedance sections of transmission line connected in series.

Filters Using Resonant Sections. As frequencies of operation are increased, the short-section coaxial filters described above become mechanically inconvenient because of the small size of the line sections, and recourse to filters involving resonant sections of line becomes necessary. A general method was developed for analyzing all types of coaxial filters, and design equations were derived for a number of band-pass and low-pass sections filters. Matrix algebra was used in the attack on the problem, and the results of the analysis were tabulated.[613] A similar analysis was performed on an easily constructed high-pass filter of this type.[614] Consideration was given to the question of spurious responses in a low-pass filter, and formulas were derived which enable the design of one type to be carried out so that some of the spurious pass bands cancel and more nearly ideal low-pass characteristics are obtained.[615] At a later date the design equations mentioned above were revised, and the new data summarized in tabular form, including the results of some additional types of filters.[617]

It was shown that the optimum response of series-coupled circuits is independent of the type of nonresonant coupling and depends only on the number of resonant cavities, the allowed mid-band loss, the bandwidth, and the center frequencies.[616] Universal curves were drawn for such circuits for the case of optimum response. The results hold equally well for lumped circuits.

General Properties of Filters. The problem of filter pass-band loss due to mismatch in receiver r-f lines was considered.[697] A filter operates properly only if it is terminated at both ends in the impedance for which it was designed. Formulas and curves were derived for the maximum and minimum possible mismatch and insertion-loss values; the results showed that the standing-wave ratios of the receiver input and of the antenna should be kept lower than is commonly supposed, if filters are to be used.

A study was made of the universal characteristics of triple-resonant band-pass filters.[738] The universal insertion-loss characteristic was calculated as a function of frequency for a band-pass filter composed of one, two, or three lossless resonant circuits in a loosely coupled cascade connection between a source and a load impedance. Consideration was given to the effect of load and source coupling upon pass-band insertion-loss variation and upon bandwidth. The results were summarized in the form of universal response curves for filters of this type.

6.4 MISCELLANEOUS THEORETICAL INVESTIGATIONS

In addition to the studies reported in the foregoing sections, there were a number of investigations, mostly rather brief, which cannot be included in the major classifications above. These included an analysis of the operation of magnetrons, studies of the probability theory involved in making radar intercepts with search receivers, calculations of jamming effectiveness, and so forth.

[redacted]

6.4.1 Magnetron Studies

Not much theoretical effort was expended on magnetrons in Division 15; some work was carried through, however, in particular on the study of space-charge limited, single-stream solutions in a cylindrical magnetron with small current (see also Chapter 3).

The complete first-order solution for the radial motion of the electron was found to be

$$R = \frac{r}{r_c} = R_0(t) - \frac{\epsilon(t_0)}{2}\left(\frac{\omega}{\omega_1(t)}\right)^{\frac{1}{2}} \sin \Theta - \int_{t_0}^{t} \frac{\ddot{R}_0(t')}{\sqrt{\omega_1(t)\omega_1(t')}} \sin(\Theta - \Theta')\, dt' \quad (108)$$

where

$$\epsilon(t) = \frac{4eI(t)}{mr_c^2\,\omega^3}, \quad (109a)$$

$$\phi(t) = \omega \int_{t_0}^{t} \epsilon(t')\, dt', \quad (109b)$$

$$R_0(t) = [\,\phi(t) + \sqrt{1 + \phi(t)^2}\,]^{\frac{1}{2}}, \quad (109c)$$

$$\omega_1(t) = \frac{\omega}{2}\left(1 + \frac{1}{R_0^4(t)}\right)^{\frac{1}{2}}, \quad (109d)$$

$$\Theta(t) = \int_{t_0}^{t} \omega_1(t')\, dt', \quad (109e)$$

$$\Theta - \Theta' = \Theta(t) - \Theta(t') = \int_{t'}^{t} \omega_1(t'')\, dt'', \quad (109f)$$

where all quantities defined in equation (109), with the exception of $\epsilon(t)$, depend on t_0 as well as upon those other quantities which are explicitly stated. In equations (108) and (109), r is the distance of the electron from the axis, t is time, r_c = cathode radius, and $\omega = eH/mc$. In this latter, e is the electronic charge, m its mass, c the velocity of light, and H the applied static magnetic field. The motion of the electron is also subject to a radial electric field $E = E(r, t)$. The quantity $I(t)$ is the current per unit length through the magnetron, consisting of the sum of the electronic and displacement currents, and is a function of the time alone, independent of r.

Brillouin's theory of the plane magnetron[842] was extended to cylindrical magnetrons, on the condition that the current I is small enough so that

$$\epsilon(t) = \frac{4eI(t)}{mr_c^2\,\omega^3} << 1. \quad (110)$$

This restriction is generally well satisfied under normal conditions and does not require the current to be unreasonably small.

Results of Analysis

The analytical method developed[657] allows an expansion in increasing powers of ϵ and was explicitly carried out to include the linear terms, giving in this approximation the distance of an electron from the cathode as a function of time in terms of simple integrals and with the current I an arbitrary function of time. As in the above-mentioned theory, it was assumed that the solutions are of the single-stream type where all electrons which at a certain time are found at a given position have the same velocity. It was then investigated under what conditions this original assumption is justified, and it was found that the conditions for a single-stream solution are not nearly so general as they seem to appear from the plane case.

In the first place, it was found that an original single-stream solution can break down sooner or later, depending entirely on the time dependence of the current. In the second instance, any single-stream solution established while a positive current was flowing breaks down a sufficient time after cessation of the current. This indicates the possibility of transitory multiple-stream states, at least in certain cases, and, without adequate methods for their investigation, precludes any safe conclusions concerning the ultimate stationary state which must be reached if the anode voltage, after having increased from zero to a certain value, is held fixed.

6.4.2 Search Receiver Probabilities

In connection with the problem of the best design and method of operation for radar search receivers, the question arose of the probability that a receiver sweeping in frequency would intercept a radar with a rotating antenna—in other words, the probability that the receiver frequency would coincide with that of the radar (within the receiver bandwidth) at the same time that the radar antenna was pointing toward the receiver. The problem was complicated by the fact that the antenna of the search receiver was sometimes directional and rotating. A number of studies were attempted. The rigorous

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solution of the problem proved quite elusive, although some special cases of interest were treated successfully.

Rigorous Analysis

Some work was also done on the problem of simultaneous periodically recurring events,[674] in which formulas were derived for the probability that two events, each recurring with a definite period and lasting for a definite length of time, occur *simultaneously* at least once in some given time interval. The further condition may be added that the simultaneous occurrence itself must have at least a given minimum duration.

Approximate Solutions

An adequate engineering approximation to the intercept problem, while not rigorous, was also constructed, characterized by comparatively simple formulas and theory. It was felt that the results were adequate to predict the performance to be expected with sufficient accuracy, and this belief was confirmed by experiment.

Theoretical Analysis. The one important thing from an operational standpoint is what we may call a "characteristic" time t_0 which determines the time scale against which a more or less universal probability curve can be plotted. In other words, the probability P of interception by time t may, for rough practical purposes, be taken of the form

$$P = f\left(\frac{t}{t_0}\right),$$

where f is a universal function. The important quantity is obviously the constant t_0 which governs the time scale. The formula for t_0 is

$$t_0 = \frac{T_R T_S T_A}{\left(\frac{B_R}{360}\right) T_R \left(\frac{A\%}{100}\right) T_S + \left(\frac{B_A}{360}\right) T_A \left(\frac{A\%}{100}\right) T_S + \left(\frac{B_R}{360}\right) T_R \left(\frac{B_A}{360}\right) T_A}, \tag{111}$$

where T_R, T_A, T_S are respectively the periods, in seconds, of the enemy radar, of our antenna, and of our sweep. Also B_R and B_A are respectively the beamwidths, in degrees, of the enemy antennas and our antennas, while $A\%$ is the acceptance percentage of our receiver. It is assumed that our apparatus has been designed with reasonable intelligence, so that particular antenna directions are not excluded because of correlation between the sweep and antenna periods. There is no doubt but that for small values of P or t/t_0, the function $f(t/t_0)$ is merely t/t_0, since then questions of redundant probabilities, overlaps, etc., do not enter. When P gets somewhat larger, say, in the vicinity of 50 per cent, there are more complications involved in the determination of the theoretical probability.

A distinction can be made between three cases, which can be characterized respectively as the monochromatic, uncorrelated, and "ignoramus" cases, as follows.

1. In the *monochromatic case* it is supposed that the enemy radar has a perfectly definite frequency. The theoretical curve of probability of finding the enemy within a time t is then a series of straight lines, each segment with lower slope than the preceding. The reduction in slope after a certain time is due to the phenomenon of overlap. In case the problem is only one of two coincident events (omnidirectional antenna or 100-per cent acceptance bands), it has been shown that there should be only two segments of appreciable length. The points at which the breaks occur are conditioned by the relations of commensurability between the various periods, and this is what makes the phenomenon potentially so complicated. If the enemy frequency happens to have just the right value, the slope of the curve can be horizontal after a certain value of the time, so that the maximum achievable probability is less than 100 per cent (under 50 per cent in certain cases). Of course the probability is zero that the enemy frequency will have one of these particular values, but there are certain small ranges of frequencies such that we cannot be sure of intercepting the enemy in, say, 1,000 years. Obviously, the chance of the frequency being in such a critical zone is negligibly small, and what is needed is a theory that allows in a reasonable way for uncertainty in the enemy frequency.

2. A procedure which attempts to allow for the uncertainty is provided by the *uncorrelated model.* Here it is assumed that the probability of finding an event in a time interval t to $(t + dt)$ is independent of t, except for a "cutout" factor

SECRET

$(1 - P)$ which allows for the fact that we do not count an interception as new if one has already been made. The appropriate differential equation is thus

$$\frac{dP}{dt} = \frac{t}{t_0}(1 - P),$$

of which the solution is

$$P = 1 - e^{-t/t_0}, \qquad (112)$$

with t_0 as in equation (111). The quite valid objection was raised against this formula that the ideas on which it is based are too naive. Specifically, no cognizance is taken of the fact that the overlapping or commensurability phenomena may make the probabilities dependent on time.

3. Obviously, what is needed is what may be characterized as an *ignoramus* theory. Here it is assumed the ignorance of the enemy frequency is great enough to embrace all possible cases of tuning and detuning with respect to commensurability relations. We then make a calculation with the monochromatic theory, but average the results over different values of the enemy frequency so as to have all commensurability and incommensurability situations. This was attempted, with the help of previous results and with certain none-too-good approximations made in connection with the averaging. Also it must be assumed that the enemy beamwidth is not too large, and that the time our antenna is "on target" is small compared to that during which the enemy is sweeping through us. The calculation gives the following formula for the probability

$$P = \tau - \frac{1}{4}\tau^2, \quad (\tau \leqq 1),$$

$$P = -\frac{1}{2}(\tau - 1)^2 \log\left(\frac{\tau}{\tau - 1}\right) + \frac{1}{4} + \frac{\tau}{2}, \ (\tau \geqq 1), \qquad (113)$$

where $\tau = t/t_0$, with t_0 as in equation (111).

The results of equations (113) and (112) (the ignoramus and uncorrelated theories) are compared in Figure 38. It is seen that the differences between the two theories are inconsequential

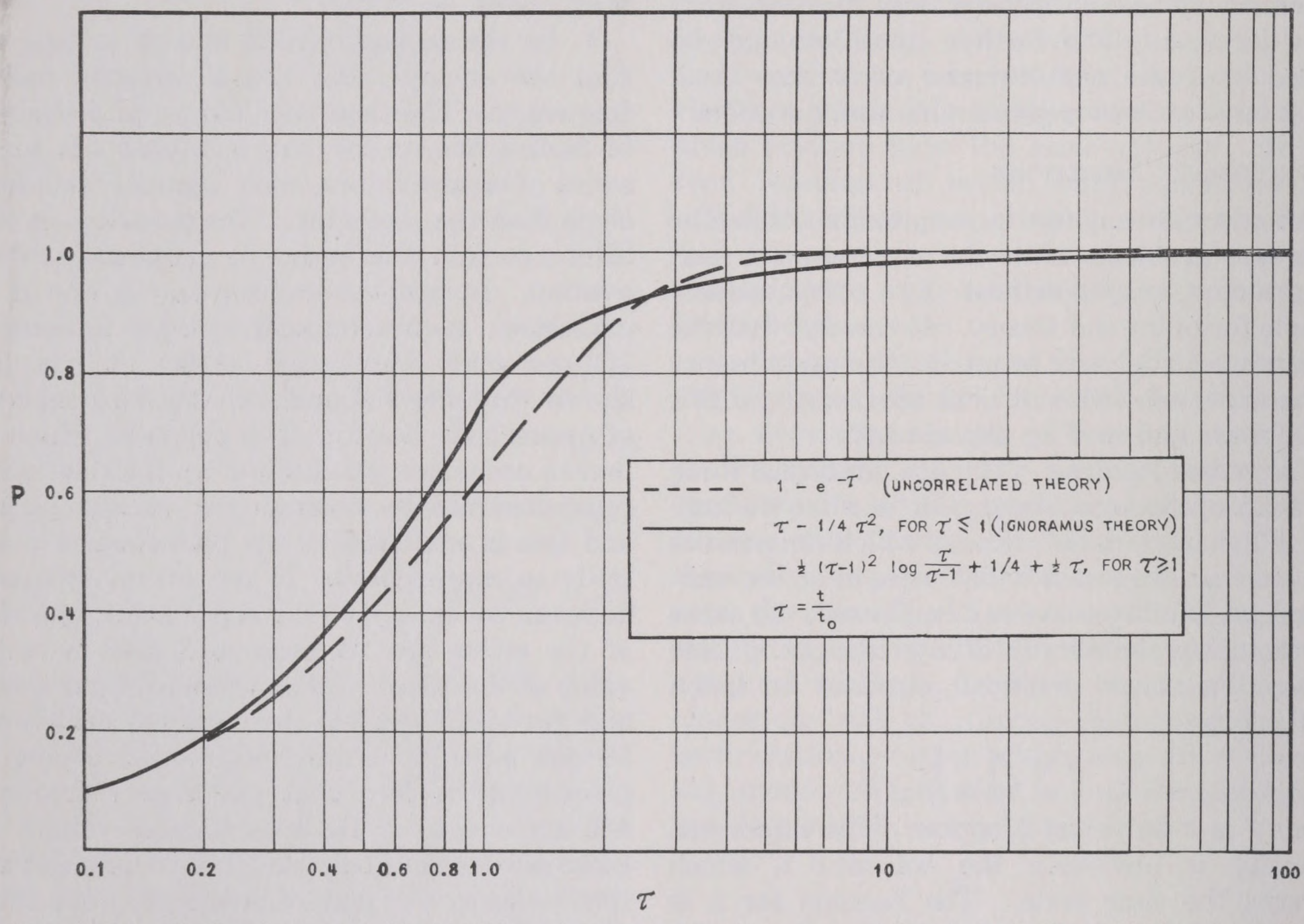


FIGURE 38. Radar intercept. Probability of success in time τ as a function of Tan. Comparison of uncorrelated and ignoramus theories.

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compared to other operational difficulties and uncertainties. As would be expected, the ignoramus theory gives lower probabilities for large values of the time, but somewhat higher probabilities in the intermediate zone, as the commensurable cases tend to inhibit interception for certain kinds of tuning, but do not become operative until a certain time has elapsed. It is not surprising that the two theories should agree

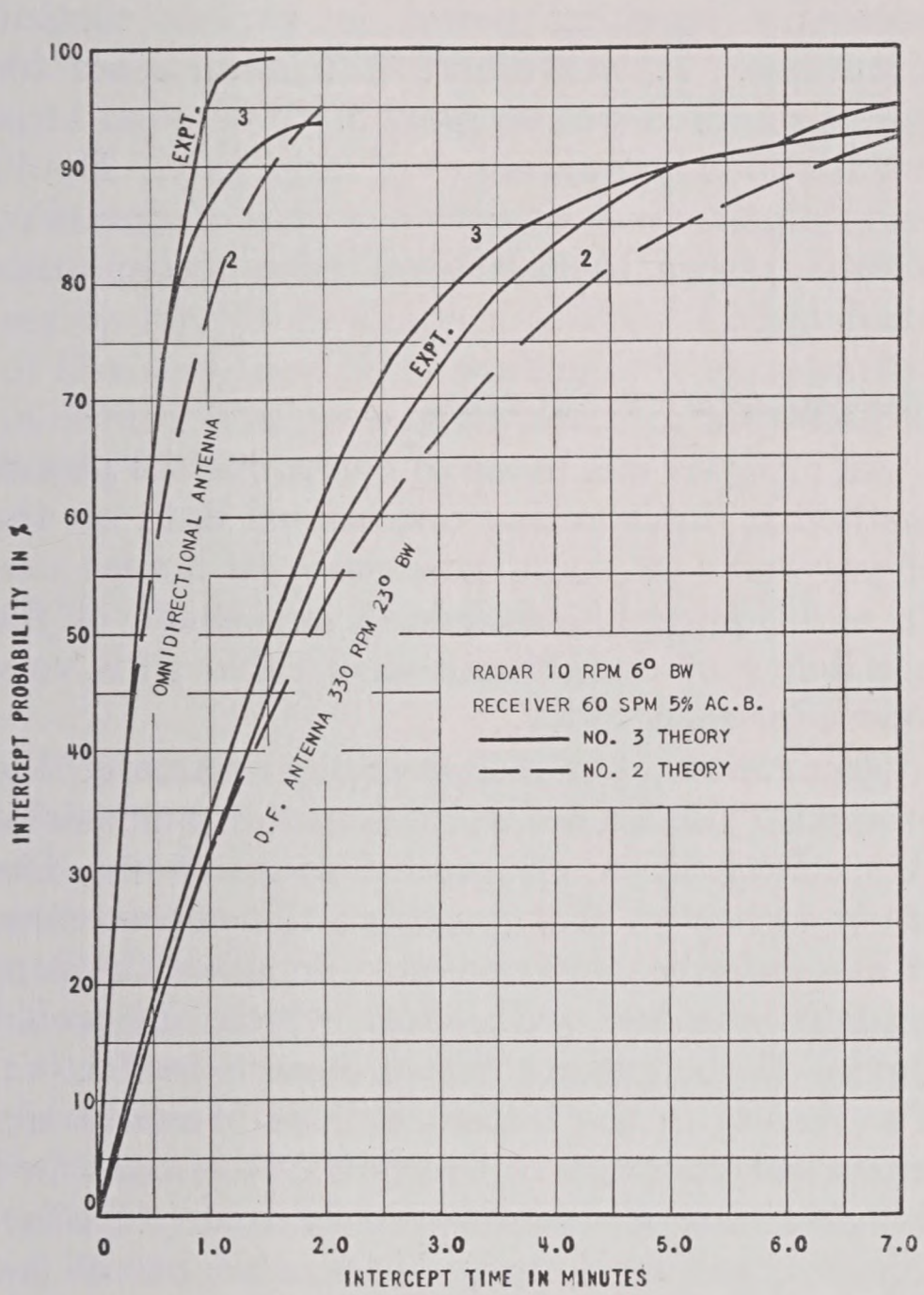


FIGURE 39. Intercept probability effect of direction-finding antenna; comparison of the various theories with experimental results.

quite well from a qualitative standpoint, as averaging over the various possible values of the enemy period tends to smooth over the various correlation effects due to much or little commensurability. Still it is to be emphasized that the two theories are not identical, as averaging over different amounts of commensurability is not equivalent to omitting correlation entirely.

Comparison with Experimental Results. On the whole, either equation (112) or (113) reproduces quite well the results obtained experimentally by motor-driven devices for recording coincidences.[766] Figure 39 is a typical case, although the agreement is not quite so good for some of the other examples. The uncorrelated and ignoramus forms of theory are indicated respectively by dashed and solid lines. For low values of the probability, the theory and experiment should agree exactly, as in this zone sufficient time has not elapsed for questions of correlation to enter, and all forms of theory are the same. It is not clear why the experimental curves, while agreeing quite well with the uncorrelated and ignoramus theories, do not agree at all with what one would obtain with a monochromatic theory. Ideally, one knows all the periods involved, so that the experimental model should behave in a monochromatic fashion. If the experimental data were taken completely at face value in, for example, the omnidirectional case of Figure 39, the periods are exactly in the ratio 6:1, and after six sweeps nothing new would be found, so that the saturation value of the probability would be in the neighborhood of 10 per cent. To explain the fact that actually no such saturation is found, it is necessary to suppose that the recorded periods are only accurate to 2 per cent or so. In some of the other examples the deviations in frequency required to destroy commensurability are even smaller. If the frequency fluctuated from one sweep to another, one might expect the uncorrelated theory to apply, whereas if it varied only from one run to another, the ignoramus form would be the more suitable. One would conjecture that the former situation was more likely to arise experimentally, but the latter model seems to agree somewhat better with the experimental results. The fact that small deviations in frequency obliterate the commensurability relations makes one suspect that even if one knew the enemy frequency, the monochromatic assumption would not apply as well as the other, more statistical forms of the theory.

[6.4.3] Operational and Miscellaneous Studies

A number of problems received only very brief theoretical treatment, although some of them were of considerable operational significance. Included among these were several calculations of the jamming effectiveness of proposed counter-

measures, as well as some miscellaneous investigations.

Jamming Effectiveness Calculations

Theoretical calculations were made on the jamming effectiveness of various proposed RCM devices, methods, and techniques, in some cases to check on minimum jamming distances or similar points, in other cases to decide whether the proposed countermeasure was worth using at all.

Radar Chicks.[m] One such study was concerned with an estimate of the practicability of using expendable jammers (Chicks) for radar countermeasures purposes.[555] Three types of Chicks were considered: parachute-borne jammers to screen during the period of fall, floating jammers for the screening of small boats and barges, and grounded jammers to be dropped from planes into enemy territory. The effects of floating Chicks were compared to those of corner reflectors (see Section 6.3). The results, based on the available data as of September 1943, indicated that:

1. Parachute Chicks appear to be of practical use against ground-controlled interception [GCI] or gun laying [GL] in raids against isolated targets whose location and frequency are accurately known; in other cases too large a volume and weight are required.

2. Parachute Chicks are not useful for screening boats, except possibly those of higher speed.

3. Parachute Chicks are not effective against aircraft interception [AI].

4. Parachute Chicks could be used against early-warning [EW] radar.

Floats carrying either corner reflectors or Chicks could be useful in screening barges and small boats, whereas grounded Chicks appear to have only a nuisance value and are generally impractical for RCM purposes.

Effectiveness of GCI Jammers. In the summer of 1943, calculations were made[807] to determine the effective ranges of two high-power ground transmitters designed to jam the German GCI system. One of these was on 40 mc (Cigar) for use against the ground-to-fighter communications, the other (Tuba) on 500 mc to jam the AI radar. It was concluded (to summarize the results in a very general way) that these transmitters would be effective at ranges up to 200 miles, under optimum conditions, if sufficiently high antenna gains were used.

Jamming of Radio Altimeters. A study[450] concerned with jamming the German FG101, FG101A, and FG103 radio altimeters was undertaken in the early months of 1944. On the basis of the best information available at the time, an attempt was accordingly made to determine the necessary jamming power in various tactical situations. It was found that in all cases the power required was so great as to demand large installations and antennas of large gain. Doubt was expressed as to the value of jamming piloted planes if such installations were made available.

Miscellaneous Studies

An analysis was made to determine the proper method of interpreting operational data on the effectiveness of countermeasures in actual use. In addition, an investigation was made of the possibility of designing a steel cable with very low radar reflectivity.

Operational Analysis Methods. Among the otherwise unclassified studies was an analysis of the effectiveness of countermeasures.[643] The study indicated that to judge the effectiveness of a countermeasure one must compare the data actually obtained with those which one would expect if the countermeasure were ineffective. The results in the latter case are of essentially statistical character. Procedures are described for obtaining a quantitative estimate of effectiveness, and for judging the significance of the result.

Low-Reflectivity Cable. A miscellaneous problem of some interest was the design of an armored steel cable with low radar reflectivity,[715] for use in the target practice of radar-controlled antiaircraft guns. On such practice, an expendable flying radar target is needed. A target of this kind can be obtained by towing a nylon sleeve behind an airplane and either attaching, close to the sleeve, a small corner reflector or weaving a great number of half-wave dipoles into the sleeve. It can easily be made to have a cross section equal to that of an airplane and would be perfectly adequate except for disturbing radar returns, originating from the cable by which the target is towed behind the plane. Accordingly,

[m] See Chapter 8 for discussion of communications Chicks.

a special cable was developed. It works on the principle of a transmission line with periodically varying self-induction and has the property that its (radar) cross section is about five times smaller than that of a continuous steel cable of the same dimensions. The theory and design of the cable were worked out, and laboratory tests were made on manufactured samples.[715]

6.5 MISCELLANEOUS DEVELOPMENTS AND RESEARCH STUDIES

It was found necessary to carry on a variety of unrelated miscellaneous developments and research studies in support of the RCM program of Division 15. These were mainly experimental in nature. The more important ones are described briefly below.

6.5.1 Use of Models in Antenna Investigations

It is theoretically possible to construct a model of an electromagnetic system which is an exact simulation of the prototype. The simulation will be exact if the dimensions of the model are made $1/n$, if the dielectric constants are unchanged, and if the frequency and conductivities are n times those of the prototype, where n is an arbitrary scaling factor.

Methods for measuring the patterns of antennas by means of models have been investigated to obtain information needed in designing antennas having specified patterns. Most emphasis in the investigations has been placed on aircraft antennas.

Methods for Measuring the Patterns of Model Antennas

The methods used for measuring the patterns of full-scale antennas are in general applicable to measurements on a model. However, the accessibility and convenience of handling a model result in differences in the equipment and technique employed. The methods which have been investigated on models may be broadly classified as follows.

Method I: Direct Measurement of the Pattern as a Transmitting Antenna. In this method a transmitter is used to excite the model antennas. A receiver with an antenna arranged to measure the desired component may then be used to explore the field radiated by the model.

Method II: Direct Measurement of the Pattern as a Receiving Antenna. This method is similar to the above, except that the transmitter is used to explore the sensitivity of the model antenna as a function of direction. By virtue of the reciprocity theorem, the pattern so obtained is similar in shape to the corresponding pattern measured when the model antenna is transmitting.

Method III: Measurement of the Reradiation from a Receiving Antenna. This method is essentially a combination of the previous two methods. A remotely located transmitting antenna is excited by an unmodulated transmitter sending a wave toward the model. This wave induces currents in the model antenna which are a function of the impedance connected to its terminals. If the termination impedance is made to vary periodically, the field reradiated from the model antenna will also vary periodically. The resultant modulation permits the reradiated field to be distinguished from the primary or exciting field. In practice, the reradiated field which returns along the transmitted ray (i. e., the echo) is measured. The pattern obtained in this way is the product of the pattern for reception by the pattern for transmission. Since these are similar, the measured pattern is the square of the antenna pattern.

Airborne Antennas

One of the principal problems to be solved in designing equipment for making pattern measurements on antenna models is that of controlling stray reflections. Avoidance of distortion of the pattern by reflections from the ground is particularly important. The obvious procedure is to elevate the equipment and use sufficient directivity at the measuring antenna to minimize the pickup of ground reflections. Another method uses the earth as part of the directive antenna at the observing position.

Most of the investigations of models of airborne antennas have been made in the frequency range 500 to 10,000 mc. In this region it is possible to control ground reflections with a highly directive antenna at the observing position

while keeping the equipment at a reasonable height (8 to 10 ft) above the ground. The directive antenna usually consists of a pyramidal horn of rectangular cross section, designed to have equal directivity in its two principal planes. Such an antenna is easy to feed over a wide frequency range and has linear polarization and adequate directivity. At frequencies less than approximately 500 mc, it becomes difficult to control ground reflections with equipment of reasonable size.

The model is mounted on a tower located at a distance from the horn aperture which is sufficient to insure that the field is essentially uniform over the region occupied by the model. The minimum distance which can be used depends on the size of the model and other factors. The tower which supports the model must be carefully designed to minimize distortion of the field.

For frequencies less than about 2,500 mc, the physical size of oscillators which are presently available make it impractical to mount the oscillator in the usual sizes of models. Above 2,500 mc, certain types of oscillators (klystrons and other veolcity-modulated oscillators) are compact enough to mount in the model, provided leads can be used to conduct power supplies located at the observing position. These leads have to carry voltages which may run as high as 2,000, so that it is preferable to use other measuring techniques, if possible. However, this technique seems to be the only practical one for K-band frequencies.

Method II has been found to be the most useful method for the frequency range 500 to 10,000 mc. The transmitter used to excite the horn located at the observing position may be any convenient oscillator of suitable frequency and power capability. If the transmitter is tone-modulated, a very simple receiver consisting of a tuned crystal or bolometer detector may be used in the model. The audio output of the detector is conducted to the observing position by wires which are so located in the field as to produce minimum distortion of the model antenna pattern.

Method III has a number of disadvantages which limit its usefulness. The principal limitation is lack of a suitable modulator for use in the model. The only type which was tested consisted of a special vibrator with contacts to open and close the antenna circuit. The vibrator was not sufficiently stable mechanically and produced very little modulation at frequencies above 2,000 mc. An alternative modulator using nonlinear impedances (crystals, for example) which are made to vary periodically by suitable biasing arrangement, has been considered but not tested. The principal disadvantage of the method, however, is the need for a phasing adjustment before each reading is taken. This makes automatic recording of the pattern impractical. Further, any lead wires to the model will distort the pattern even though they are shielded.

For frequencies below 500 mc, ground reflections can be best controlled by arranging the equipment to operate vertically instead of horizontally. The ground then becomes part of the antenna system at the observing position. Method I is probably the most useful one in this frequency range. Battery-operated transmitters of small physical size can be readily constructed for installation in the model. A standard superheterodyne receiver with a short dipole or vertical-loop antenna can be used on the ground directly beneath the model. The reflection of the transmitted wave at the ground will produce standing waves which may distort the pattern. If the model is small in terms of wavelength, it may be located at a maximum in the standing wave. Alternatively, a high impedance inserted in series with the antenna lead in the model will minimize the distortion by reducing the variation in circuit impedance due to the reflected wave.

At low frequencies, Method II is probably not too useful since the model will, in general, be too small in terms of the wavelength to shield properly the lead wires from the model to the observing position. Method III has not been tested at these low frequencies but should be useful. It is probable that the phasing adjustment need not be made with each reading when the model is small in terms of the wavelength.

The use of some form of automatic recorder at the observing position has been found to be highly desirable. An Esterline-Angus strip-chart recorder is very convenient and rapid, but gives a presentation which is not so readily interpreted as a polar presentation. A hand-operated mechanical transcriber has been constructed for converting the strip-chart record to polar form.

A specially constructed polar recorder has been obtained from Leeds and Northrup and found to be very satisfactory. Recorders can be synchronized with the rotation of the model by selsyns or equivalent devices. The bolometer and crystal detectors used as receivers are approximately square law so that the range of signal to be recorded is rather large. A special amplifier[48] with a square-root characteristic has been designed to provide compression for recording.

In modeling an antenna for pattern measurements, ordinarily it is not necessary to have an exact simulation of the physical details. Details of the prototype which are small in terms of the wavelength are usually not important. Many types of antennas have been measured with models.[26-39, 44, 47, 55] It has also been found feasible to model simple antenna arrays[32] and systems.[50-53]

Models have been used for measuring propeller modulation.[11] A method for measuring the ellipticity of the polarization radiated from an antenna, including the direction of rotation of the electric vector around the ellipse, has also been developed. Development of methods for investigating direction-finder antennas has also shown considerable promise.

Shipboard Antennas

Methods and techniques[56] for measuring the patterns of ship-borne antennas by means of models were investigated. The problem is not essentially different from the aircraft problem except for the effect of the sea.

For frequencies below about 100 mc the sea acts like a perfect reflector for all practical purposes. Hence it can be simulated by constructing an image of the ship and feeding the antenna and its image with currents of the proper phase and magnitude. Alternatively, the sea may be simulated by a large metallic area, with the ship model located near its center. It is essential to terminate the edges of the metallic area in such a way as to reduce the reflection from the edge discontinuity. One method[26] is to serrate the edges and place poorly conducting material between the serrations. An improved method[77] employing special absorbing screens was also developed.

Ground-Based Antennas

The simulation of the effect of a finitely conducting earth is perhaps the most difficult problem in modeling antennas. Theoretically, the earth could be simulated by using a material of conductivity n times that of the earth and a dielectric constant which is unchanged. Actually, such a material is not readily obtained. Even if such a material were available, a thickness of quite a few feet would be needed in order that the wave reflected from the underside of the section would be sufficiently absorbed.

It is sometimes possible to avoid the problem of simulating the ground. For example, if the frequency of the prototype is low enough, it may be possible to assume that the earth is a perfect conductor, in which case simulation may be obtained as with the sea. On the other hand, if the frequency is high enough and the structure on which the antenna is located is large enough, it may be possible to measure the pattern with the model of the antenna and mounting structure in "free space." The effect of the earth on the pattern may then be estimated from theoretical considerations.[10]

Model Methods for Measuring Antenna Impedances

An investigation[11] was carried out to determine the feasibility of measuring the impedances of antennas by means of models. For an accurate simulation of the antenna impedance, it is necessary to make the model with great care. The principal difficulty is in modeling the base of the antenna, with its associated connectors, etc., which has a much larger effect on the impedance than on the pattern.

6.5.2 Use of Models in Studying Radar Echoes

For investigations of echoes from targets it is not always feasible to use actual radar equipment with full-scale targets. The lack of control over the target orientation is particularly bothersome in measurements on aircraft in flight. For these and other reasons, it was found desirable to investigate the possibilities of using models.

The usual pulse technique used in radar equip-

ment is not suited to model measurements because of the difficulty in obtaining pulses of sufficiently short duration to permit working at close range. For this reason, other methods for measuring the echo were tried. Separate transmitting and receiving equipment can be used, with the antennas placed as close together as possible. Such an arrangement is useful for some measurements, but suffers from the disadvantage that the path of the echo ray does not coincide with the path of the transmitted ray, as in actual radar operation. A method for avoiding this has been developed in which the transmitter and receiver use a common radiating system. A horn is used with the transmitter excitation connected in the usual manner. The receiver is connected to an antenna array which is located inside the common wave guide. The array used for most of the measurements has consisted of one cylindrical stub connected to the receiver, and two parasitic stubs spaced about ⅛ wavelength each side of the main element and located on the center line of the wave guide. It was found to be possible to adjust the lengths of the parasitic elements to give practically complete suppression of the outgoing wave at the receiver terminals, while retaining sensitivity to incoming signals.

Several methods for calibrating the equipment have been developed. A number of spheres were tested to determine the relative variation of echo area with radius. It was found that the curve of variation had the same relative shape as predicted theoretically. It seems to be a safe assumption, therefore, that the computed echo area will be correct. A second method of calibration was tried in which circular and square plates were used. The echo area computed on the basis of geometrical optics was assumed to be correct for plates whose edges are long in terms of the wavelength.

Measurements[45, 46] have been made of the echo patterns of large bombers at 200 mc. Methods for investigating the propeller modulation of radar echoes have been investigated. The patterns[40-43, 49] of several sizes of corner reflectors have been measured. Measurements[54] of the echoes from tow cables have also been made.

6.5.3 Magnetron Filament Regulator

Back heating in magnetrons tends to overheat the magnetron cathode and may shorten its life considerably. The deleterious effects of back heating can be minimized if the power applied to heat the cathode is decreased by an amount equal to the power supplied by back heating. A circuit has been devised to provide this compensation electromechanically, in which the primary of the filament transformer is one arm of a self-balancing impedance bridge. Use of a step-up transformer in the comparison arm of the bridge permits the application of about 90 per cent of the line voltage across the filament transformer without loss of bridge sensitivity. Immediate conversion to direct current of the a-c signals across the arms of the bridge makes the circuit frequency-independent. The bridge difference-voltage is amplified in a pentode whose output actuates a differential relay. This relay in turn operates a reversing motor which adjusts the Variac supplying the primary voltage to the bridge. The motor runs until the filament resistance reflected through the filament transformer is restored to within 3 per cent of the value for which the system has been preset.

Several of these regulators have been built and are in use in magnetron test sets and life-test racks.

Regulators of this type can be used as line-voltage regulators for loads of any magnitude if the primary of the filament transformer is replaced by a dummy load whose resistance is a function of current (e. g., a lamp bulb).

Some difficulty was experienced with the magnetron filament regulator because of hunting. This difficulty was eliminated and critically damped operation achieved by the inclusion of a tachometer feedback circuit associated with the motor which drives the Variac.

6.5.4 Study of Electron Paths in Magnetrons and Triodes

The General Electric differential analyzer can integrate the equations of motion of an electron in crossed electric and magnetic fields and can plot out the electron path in two dimensions automatically.[152] Simultaneous plots can be obtained of electron velocity components as functions of time and of currents induced in electrodes. Alternating electric fields can be

included and transit time effects analyzed. The one limitation of this procedure lies in the fact that space-charge effects cannot be included. However, many of the operating characteristics of h-f tubes can be deduced more or less quantitatively, even if space-charge effects are neglected.

Electron paths in split-anode magnetrons have been run under a variety of conditions. The analyzer shows in a very striking fashion that electrons tend to synchronize with the forward rotating component of the electric field over a wide range of frequencies. They do this by spiraling in small loops and "waiting" for the field to catch up with them. Several secondary electron paths starting on the anode face have been traced and the suspicion that secondary emission may act as a serious load on a magnetron has been supported. Further work which it is hoped can be run on the analyzer includes the tracing of paths of electrons which escape through the anode shields and a study of the a-c level necessary for synchronization of electrons. It is hoped that the latter study may throw some light on the troublesome failure of magnetrons to oscillate at low power levels.

The problem of electron paths in parallel-plane triodes is, of course, even simpler for the analyzer than the magnetron problem, although it is still too complex for analytical treatment. The parallel-plane triode geometry has been set up and a number of electron paths have been traced. Three important conclusions have emerged from a study of these paths. First, it has been shown that attention to the impedance levels of the external circuits should yield much higher operating efficiencies than have been obtained experimentally. Second, it is now clear that rather high peak emission is required periodically from the cathode. It is possible that the cathodes which have been used have not been capable of emitting these high currents. Third, the grid-anode transit time has proved to be more important than was expected. It would appear that inclusion of a screen grid might result in materially increased efficiency. Other minor unknowns have also been removed—the area of the cathode which is inactive because it lies in the shadow of the grid wires has been delineated, and the cathode back-heating phenomenon which appears at high frequencies is now attributable to electrons returning at a particular phase of the a-c wave.

It seems evident that the differential analyzer will prove to be a very powerful tool in the design of future microwave tubes, since it provides a fast and accurate method for solving problems which would be hopeless analytically. Moreover, a complete energy balance can be set up and energy losses can be tracked down to the basic components and phenomena with which they are associated. Information of this type can rarely be obtained experimentally.

6.5.5 Gold-Copper Alloy Solder

In assembling metal vacuum tubes with copper parts, most of the solder joints are usually made with silver-copper eutectic solder, melting at 778 C. Frequently, it would be desirable to do the soldering in several steps if only a solder were available whose melting point lay between 778 C and the melting point of copper, 1,082 C.

Alloys are to be avoided which are low in copper and dissolve copper out of the tube parts to form eutectics, or which have long plastic ranges or brittle phases. These considerations exclude other silver-copper alloys than the eutectic but suggest the use of gold-copper alloys having more than 60 per cent copper (by weight).

The combination 62.5 per cent copper, 37.5 per cent gold has been chosen as being safely clear of brittle phases and having a useful melting range (950 to 980 C). Soldered joints[136] made with this alloy at a furnace temperature of 1,040 C are vacuum-tight and mechanically strong.

This alloy is equally satisfactory for soldering Fernico to copper. Unlike silver solders, it does not penetrate appreciably into the grain boundaries of the Fernico.

In wire form this alloy can be used in making copper-to-copper diffusion seals. The seal formed by baking under pressure for 2 hr at 450 C is vacuum-tight and seems to be stronger mechanically than pure gold diffusion seals.

6.5.6 Analysis of Behavior of Homing Missiles

An analytical study[141] was made of the behavior of missiles designed to home on radar

SECRET

stations by translating information received at an antenna array (two Adcock antennas and a pair of crossed dipoles) into motion of control surfaces (rudder and ailerons). The behavior of the missile was assumed to be such that the controls follow instantaneously the instructions received from the antenna array. An investigation was made of the effects on the missile of field distributions from ground reflections or other spurious radiating sources. The results are applicable to homing systems and radio direction-finders in general.

6.5.7 Meteorological Observations for Propagation Studies

From December 20, 1944, to February 27, 1945, and again from August 1 to September 30, 1945, meteorological observations were made near Hadley Airport, New Jersey, to obtain data for correlation with propagation in the 2X and X bands. This work was initiated at the request of the NDRC Committee on Propagation. The transmitters were located on the top of a tower at Mount Neshanic, New Jersey. The meteorological observations were made at a point near the center of the propagation path.

The primary data consist of low-level soundings (up to 500 ft) made at 0200, 0600, 1000, 1400, 1800, and 2200 Eastern War Time. Temperature and humidity elements were carried aloft by a tethered balloon or by a kite. A light three-conductor cable connected the elements to meters on the ground. The sounding data were supplemented by continuous records of temperature and wind direction. A mobile Army weather station also made possible continuous records of wind velocity and barometric pressure.

The data were turned over to the NDRC Committee on Propagation for study and correlation.

SECRET

PART III

NONRADAR APPLICATIONS

SECRET

Chapter 7

NONRADAR RECEIVING AND DIRECTION-FINDING TECHNIQUES AND EQUIPMENT

7.1 INTRODUCTION

SEVERAL SPECIAL projects covering receiving and direction-finding [DF] techniques were undertaken as part of the general nonradar countermeasures program carried on by Division 15 laboratories. The receiver projects were in many cases a necessary part of the development of jamming equipment. They included not only the development of special receivers for use in monitoring enemy signals that were to be jammed, but also studies of receiver vulnerability. Most of the projects dealing directly with receiver vulnerability are to be found in Chapter 9; however, some of them have of necessity been included in this section. Special studies were made of DF schemes; some of this work is discussed in Chapter 4 of this report and some of it is discussed in this section.

The work on receiving and DF techniques was carried out at Bell Telephone Laboratories, Inc. (under contracts OEMsr-778 and 966), at the Panoramic Radio Corporation (under contract OEMsr-1138), at the Federal Telecommunications Laboratories, Inc. (under contract OEMsr-1458), at the Radio Corporation of America Laboratories (under contract OEMsr-895), and at the Airborne Instruments Laboratory (under contract OEMsr-1305).

7.2 TECHNIQUES

Division 15 work in this field included the development of general techniques and specific equipments; this section discusses techniques, and the following section, specific equipments.

7.2.1 Communications Ferrets for Searching and Monitoring

GENERAL REQUIREMENTS

In order to apply countermeasures to the enemy's radio communications circuits effectively, it is necessary to obtain certain information regarding his facilities and type of traffic. Among the technical items on which information is desired are the frequencies in use, the type of polarization, type of modulation, direction, etc. These data are needed in order to determine the type of jamming which will be most effective. It is also important to know the principal uses of a given circuit, i.e., whether the circuit is for tactical purposes, administrative use, or some other purpose. The use will determine whether it is more desirable to jam or to intercept under a given set of circumstances.

Such information can be acquired by the use of suitable search apparatus. Search receivers can be used to intercept and monitor enemy transmissions, and DF apparatus can be used for determining the direction from which the signals arrive. The search apparatus should incorporate automatic-recording features to indicate the presence of signals and arrangements for making recordings of enemy transmissions for later interpretation.

The search receivers, in addition to meeting the sensitivity and selectivity requirements of good communication receivers, should also meet additional requirements peculiar to search applications. The receiver requirements for airborne and ground installations may differ in some respects.

In either ground or airborne installations, however, the chances are that several receivers must be used to cover the wide band of frequencies to be searched for enemy transmissions. These sets will be in close physical proximity, can use common power supplies, and will be connected either to a common antenna or to closely spaced individual antennas. Under these circumstances it is important that they should not interfere with each other's operation by emitting excessive radiation from the heterodyning oscillators or beat-frequency oscillators (fundamental and harmonics); similarly, interference from such sources by

way of common power supplies must be minimized.

If enemy signals of widely different intensities are to be searched for, it is important that spurious responses in the receivers be sufficiently suppressed. The most common response of this type is the image response, but there are many others in present type receivers. Unless these responses are well suppressed, a transmission arriving with a high carrier intensity may be picked up at apparently lower intensities at several other points on the receiver and erroneously recorded as additional enemy transmissions at several frequencies. Another source of false signals may be caused by the generation of harmonics and heterodyne products as the result of nonlinear mixer characteristics when strong signals are impressed on the receiver. There is more possibility of this sort of trouble when the receiver input is untuned (as when a buffer r-f stage is used to reduce oscillator radiation) than when it is tuned. Ordinarily this trouble will not occur unless the receiver is located close to a powerful transmitter.

Search receivers should incorporate good noise suppressors, such as the Lamb type. The dials should be accurately calibrated for direct frequency readings, or means for frequency calibration should be provided. Receivers for ground use should be conservatively designed to operate continuously without overheating, and those for airborne use should be designed to meet severe mechanical stress requirements and to operate satisfactorily under extremes of temperature variation. It is desirable that S-meter readings, or their equivalent, be reasonably related to the input signal intensity and that provision be made for a panoramascope attachment for aid in determining the type of modulation of the enemy transmission and for guarding a wider range of frequencies than may otherwise be convenient.

Communications Ferret C-1

In cooperation with Air Transport Service Command at Wright Field, the Bell Telephone Laboratories, Inc., worked on the development of the first general airborne radio countermeasures [RCM] search installation (Communications Ferret). The initial Ferret C-1 was a B-24-M aircraft equipped to search for and monitor enemy communications transmissions in the 0.55- to 300-mc band. The rear bomb bay was fitted with positions for three operators. Each operator had (1) a search receiver and recording attachment for automatically scanning a band of frequencies and recording the frequencies in use, (2) a manually operated search receiver for monitoring transmissions, (3) a voice recorder for directly recording transmissions observed on the manual search receiver, and (4) a second voice recorder for use by the operator in dictating pertinent data and other information. Additional equipment, such as panoramic receivers and adapters, was also provided to locate the frequencies of certain enemy transmissions, especially those which were of too small duration to register on the automatic recorders. The only DF equipment provided initially was for the 50- to 250-mc frequency range, and there was no equipment for determining the polarization of signals. These deficiencies should be remedied in future Ferrets.

The wide frequency band to be covered necessitated the use of three types of radio receivers, each with antennas for the particular band involved. In order to build a Ferret within a reasonable time, the receivers used in Ferret C-1 were of standard communication types and as such were not directly applicable for search use of the type contemplated. For example, with a manual search receiver of a given type on the same antenna, it was found necessary to modify the receivers to reduce radiation from the heterodyning oscillators in order to prevent mutual interference. Filters in the power-supply leads were also found necessary. The antennas also had to be designed for efficient operation over the band involved, and so located in the aircraft as to obtain reasonably good directional patterns.

Several reports were prepared which give a general description of Ferret C-1[238] (including the general layout within the aircraft and a brief description of antennas and radio equipment used) and which discuss in some detail the receiver modifications found necessary for Ferret use.[239, 240] These reports contain infor-

SECRET

mation of interest in connection with search receivers in general, and indicate the shortcomings of existing apparatus and corrective measures which might well be employed in future receivers designed specifically to meet search requirements.

7.2.2 Countermeasures and Anti-Countermeasures for Radio Navigation Aids

Radio aids to navigation direction finding were used extensively by the Allies and by the enemy, particularly in connection with the locating of aircraft positions during flight. Studies have therefore been made of the principles of radio navigation, including surveys of methods which were in use or which might come into use. This work provides a background both for general countermeasures studies and for more detailed consideration of countermeasures and anti-countermeasures for specific navigation schemes.

A report[242] has been prepared which includes an outline and examination of the principles and assumptions underlying meaconing[a] and other deceptive countermeasures, particularly with a view to specific applications. The report is of value both to development groups which are assigned the task of dealing with particular kinds of radio navigation schemes, and to tactical officers as a basis for judgment as to the applicability of countermeasures to situations which develop in an operational theater.

The probable effectiveness of three types of countermeasures which might have been employed against an h-f direction-finding system known to have been used by the Japanese for radio navigation has been investigated particularly from the standpoint of countering the DF system by the use of existing equipment. In the Japanese system in question, DF is conducted at land-based stations on signals from the plane, and information as to the plane's position is then communicated from a DF station to the plane. The report considers three methods of countering this system: jamming of the DF station, jamming of the plane reception of DF information, and meaconing. Use of both airborne and land-based jammers and meacons is considered.

[a] Meaconing refers to the destruction of the accuracy of a radio navigation system by deceptive transmissions designed to imitate actual radio navigational aid signals.

7.2.3 Development of Radio Direction Finders and Their Countermeasures 1.5 to 100 mc

The development of a 1.5- to 22-mc aircraft direction finder (Type NLS-694) was undertaken at the request of the Army Air Forces to determine whether satisfactory operation of a low-frequency direction finder could be obtained on board an aircraft of size comparable to the B-24 bomber.

The equipment developed[342] covered the frequency range from 1.5 to 22 mc. It consisted of a remotely tuned, rotating, shielded-loop collector, which could be mounted at the most suitable location on the plane, a receiver, an instantaneous cathode-ray tube indicator, and a frequency scanner which scanned a frequency band 100 kc wide, centered on the frequency to which the receiver is tuned. The control and indicating units could be placed at any distance from the collector unit in the plane.

Limited tests with the equipment aboard an Army C-45 transport plane indicated that, as expected, the structure of the plane itself seriously compromised DF performance at some frequencies and for some azimuth bearings. At frequencies other than the resonant frequencies of the plane structures, however, the errors were reasonably small and calibrations could be made to correct for the effects of the plane. Satisfactory performance could be secured over the larger part of the frequency coverage of this equipment.

The NLS-694 direction finder was sufficiently complete that it could be delivered to Air Forces' engineers for further tests aboard other types of planes.

No work was performed in the frequency range of 20 to 100 mc.

SECRET

7.2.4 Program of Investigation in Connection with the Deception of High-Frequency Japanese Direction Finders

PROBLEM

The purpose of this study was to recommend a field test program in connection with the deception of Japanese h-f direction finders in the frequency band 2 to 20 mc.

In order to establish these recommendations, it was necessary to study the available information on the Japanese direction finders and their operating setup and to coordinate this knowledge with the existing experience on h-f direction finders.

The factors taken into consideration before proposing a program of work are listed hereinafter.

The conclusions were not too encouraging as far as deception proper is concerned, but it was possible to propose a program for deception of the Japanese h-f direction finder after complete examination of the weaknesses in its design.

Although the essential purpose of the study was to discuss deception, a comparison of the results expected by the three methods was offered.

1. Straight jamming.
2. Meaconing.
3. Deception.

Then the study was concluded with a proposed program.[341]

PROGRAM PROPOSED

1. Investigation of the polarization of sky waves within the frequency range and for the distances involved, using transmitting antennas properly directed and properly polarized for the purpose.

2. Simultaneous development of a meaconing transmitter covering the frequency range and provided with means of frequency scanning and monitoring (in case adequate equipment is not readily available).

3. Combination of the particular transmitting antennas with the developed meacon, if the investigation of polarization effects gives satisfactory promise. If the results were not encouraging, the meacon would be ready to be used and could perform some specific work as such without the feature of deception by polarization.

It was proposed to begin investigation of the meacon system before the first step mentioned above was completed.

It was further suggested that the results of the polarization study would be helpful even if straight jamming were used, since these results might lead to systems of jamming transmission difficult to locate with the direction finder.

7.2.5 Direction-Finding Deception (Blanket)

This was a system of point-to-point communication which was designed to prevent DF of the source of signals. The system[87] employed a fixed station A that masked the transmissions of another station B by radiating a strong interfering signal, usually of noise modulation. Communication was effected by station B, whose location was to be concealed, by the transmission of short pulses synchronously timed to arrive at the desired receiver in the short gaps between the masking radiations from station A. The short pulses received from station B were regenerated into normal Morse code signals which were retransmitted at station C on another frequency, usually fairly close to that of the masking station A. Thus, station B was able to communicate with other stations through the medium of station C and could at the same time hear station C and thus monitor the retransmission. At the same time an enemy DF station located in the vicinity of, or beyond, station B would be interfered with by the masking signals from station A and would be unable to take bearings on station B. At station B the pulses were emitted during the time of arrival of the masking signals at that point, but were so timed that they would arrive at station A during the gaps in the masking signal. The proper timing depended upon the delays involved in the finite velocity of the radio waves and accordingly varied with the distance between A and B. The timing device could be calibrated in miles and was simple to adjust. A full-scale demonstration of the system was made during the months of

SECRET

November and December 1944. The masking station A and the retransmission station C were located in a Navy station in Trinidad. Station B was located on a naval ship which cruised off the east coast of the United States. These tests were very encouraging, but it was felt that certain improvements should be made before the system could be considered ready for use. It was felt that results would be satisfactory if an improvement of about 10 db could be made in the directive discrimination of the antenna on the ship so that 10 db more gain could be obtained in the direction of the shore station A.

The Naval Research Laboratory [NRL] undertook to develop this directive antenna for the ship and tests were made with the antenna installed on a ship to check the directivity of the antenna. The results of these tests indicated that the antenna which had been developed by NRL was entirely satisfactory. It was also planned to use two shore station installations covering any two of four available frequencies continuously. This would make it possible to improve security by selecting the highest satisfactory working frequency, since the highest usable frequency will tend to skip the zones where the enemy installations may be found. Equipment was developed and models produced for the two shore station installations, together with suitable improved equipment for the ship station.

Some attempts were made to simplify the system by balancing out the ground-wave radiations from the masking station A at the near-by receiving station, leaving only radiation scattered back from the ionosphere. Unfortunately, although the ground wave could be balanced out, strong scattering due to airplanes flying in the vicinity made the system unworkable, and the simplified system could not be used.

When the signals at station B were very weak, it was sometimes difficult to synchronize the pulses properly in the gap of the masking signal. To overcome this difficulty, three highly stabilized crystal-controlled oscillators were produced for maintaining synchronism of the pulses over a reasonable period of time, without reference to the gaps in the signal radiated by the masking station. The stability of these oscillators was adequate for field tests but an attempt should be made to obtain greater stability (beyond one part in ten million) by refinements in adjustment and more complete aging of the crystal units.

Operating and maintenance instructions[118] for the Blanket equipment have been prepared. It is understood that the Navy may possibly make another field test using a CV class vessel equipped with the unidirectional, horizontally polarized antenna and the improved equipment which were developed for this project.

7.2.6 Electronic Tuning for Panoramic Reception

A study has been made in connection with panoramic reception over the range 2 to 100 mc to determine the maximum f-m oscillator sweep obtainable by electronic means and the best method, principles, and limits applying to electronic tuning and tracking of r-f amplifier and oscillator stages over this range.

Maximum Frequency-Modulated Oscillator Sweep Obtainable By Electronic Means

Because of the importance of reactance networks in the tuning of oscillators and amplifiers, an investigation[303] was made of the design parameters affecting the operation of reactor circuits. The simple, single-stage RC phase net was investigated, first from a simplified standpoint, in order to arrive at a physical understanding, and then in more complex fashion, including all the factors having an effect upon the resulting reactance change. The principles and the method of attack used should be applicable, however, to a multistage net. The optimum values for the resistive and capacitive components of the phase network were determined.

Methods, Principles, and Limits Applying to Electronic Tuning and Tracking of Radio-Frequency Amplifier and Oscillator Stages

It was found, quite early in the investigation,[302] that an extended tuning range was readily obtainable by means of reactance tubes. The Q of the amplifier stages was, however,

SECRET

extremely low, and efforts were made to improve the performance. The work conducted toward this end included experiments intended to improve the Q by means of negative resistance derived (1) from the phasing of the reactor and (2) from the input amplifier tube. In both cases, the only load across the amplifier coil when the bias of the reactor tube was negative was that of the usual components plus that of the phase network. The Q in this case was normally high. When the bias of the reactor tube was not sufficient to obtain plate-current cutoff, however, additional loadings were placed on the coil, the most important of which was that due to the positive-resistive component of the tube impedance. This fact led to attempts to introduce negative resistance as an inverse function of negative-reactor bias.

In the experimental work performed for the case in which negative resistance was derived from reactor phasing, it was found that an improved Q was obtained for the low-bias end of the sweep but that it was not possible to raise the Q at the center of the sweep without adversely affecting the Q at the end.

In the case of negative resistance derived from the amplifier tube, the negative resistance was made a function of frequency and varied directly with it. The most important disadvantages of this method were that the derived negative resistance was a function of the bias condition of the amplifier tube and that a reasonable Q was not obtainable at the center frequency.

In so far as tracking was concerned, it was found that little difficulty would be experienced for the usual tracking requirements, even when several stages were used. In the matter of the Q for several cascaded stages, it was found that, although the circuit behaved as predicted and the Q increased in normal fashion, only complete disregard for the complexity of the circuits involved would warrant the use of this method for obtaining higher Q.

Conclusion

As a result of the work done on the project, it was felt[304] that the most logical step for continuance of this type of work would be to attempt to design a phase net which would have the proper impedance taper to effect the desired change in resistive components. This must be done, of course, with full consideration of possible changes in reactive components. Since the reactive and resistive components of the phase net are interdependent, the results in preliminary attempts were poor; as the proper condition of Q was approached, the sweep width was reduced.

7.3 EQUIPMENT DEVELOPMENTS

The following section discusses specific equipments developed by Division 15 to supplement nonradar RCM facilities. No description is included here, however, of the existing items which were ingeniously adapted for RCM purposes.

7.3.1 Panoramic Receiver (Panther)

A panoramic-type receiver[330] was developed to be used either for monitoring or (with suitable changes) for controlling an automatically tuned jamming transmitter. The receiver registered and held (without the use of persistence effect of a cathode-ray oscillograph screen) single or repeated pulses of r-f energy occurring in the monitored portion of the frequency spectrum.

The incoming r-f pulse was converted to an intermediate frequency of about 30 mc by means of a mixer and local oscillator. After passing through four broad-band i-f stages, a threshold limiter, and two amplitude-limiter stages, the resulting signal was introduced into the discriminator, which produced a d-c voltage proportional to the frequency deviation of the original r-f signal from the local oscillator frequency. This discriminator output was then fed into the holding circuit.

The holding circuit was as follows. A capacitor was charged through a rectifier tube from the unbalance developed across the cathode resistors of two cathode-follower tubes, one of which had its grid grounded and the other of which received the input signal. The anode of the rectifier was connected to the capacitor. (If

the cathode of the rectifier had been so connected, the capacitor charge would have leaked off more quickly through cathode leakage.) These stages were followed by a high input impedance stage which was also balanced from cathode to cathode. The holding circuit section just described was repeated, using a larger capacitor in order to obtain a longer holding period. Output was taken from across the cathode resistors of a balanced cathode-follower stage.

The holding circuit output caused a deflection on a meter calibrated in terms of the frequency of the original r-f signal. The deflection was held long enough to effect a reading before being manually reset to 0 with a push button. Pulses having time durations down to a few microseconds could thus be monitored.

An additional output terminal from the holding circuit permits the use of a cathode-ray oscillograph for observation of the envelope of a repeated pulse.

This equipment was not developed beyond the working "breadboard" stage.

7.3.2 Signal-Repeating Jammer (Peter Pan)

The initial work under this project involved the development of a complete jamming system to be used against radio-controlled guided missiles [GM]. Subsequently, the scope of the project was redefined to cover only the development of a high-fidelity magnetic-tape recorder. It was originally believed that the enemy might use guided missile control signals such that conventional jamming techniques would be ineffective. A control signal of this type, for example, would be one in which the phase relationships between a relatively large number of components are varied to transmit intelligence. Other possible signals include those in which a carrier is modulated at supersonic frequencies and those in which the carrier and the modulation are independently interrupted to produce signals which cannot be easily simulated for jamming purposes. Accordingly, a signal-repeating jammer[325] (Peter Pan) was to provide means whereby the enemy control signal could be recorded and retransmitted after a time delay calculated to cause maximum confusion. In this system, the enemy signals were to be heterodyned to a lower carrier frequency such that both the carrier and sidebands could be recorded. The recorded signal was then to be played back after a suitable time delay and retransmitted through a system including a balanced modulator, a converter to the original carrier frequency, and a linear r-f power amplifier.

Investigation of recording methods for use in the Peter Pan jammer indicated that a continuous-loop magnetic-tape recorder offered the best solution, since the record could be played back after any desired time delay without the necessity of processing or mechanical adjustment. A recorder of this type having a uniform frequency response from 400 to 2,600 c was borrowed from Bell Telephone Laboratories, Inc., and a system was constructed and successfully tested at broadcast frequencies.

At this stage of the development, concurrent analysis of recorded enemy signals indicated the use of a relatively simple control system such that the signals could be readily synthesized for jamming purposes. Accordingly, investigation of complete jamming systems was terminated and emphasis was placed on the development of high-fidelity magnetic-tape recorders suitable for use with standard communications receivers to record enemy signals, prior to demodulation, for subsequent laboratory analysis.

A consideration of the requirements for such a recorder led to the decision to utilize a continuous loop of 0.002x0.049-in. Vicalloy tape as the recording medium. The use of tape rather than wire permitted utilization of perpendicular magnetization for recording, with the advantage that a broader frequency spectrum could be recorded for any chosen tape speed. This reduced the requirements for the tape-drive and storage systems.

A recording method was adopted in which the incoming signal was heterodyned to a lower carrier frequency which fell at the center of the response band of the receiver. This system of recording greatly improved the possible fidelity of reproduction by insuring the absence of distortion, whether the phase shift through the

recording system were constant irrespective of frequency or not. In addition, this system provided means for determining such factors as carrier interruptions, type and percentage of modulation, duty cycle, and complex tone modulation.

As a further means of improving fidelity, it was decided to utilize the so-called a-c bias method of recording. In this method the recording tape is first magnetized to saturation to erase any previous recording, then subjected to an h-f alternating field to demagnetize it, and finally subjected to the signal to be recorded, which is superimposed on an a-c bias current having a frequency several times the highest frequency to be recorded.

Two recorder systems[316, 318] incorporating these features were produced. The first of these was an airborne equipment having a recording capacity of 15 sec and identified as AN/ARQ-12 (XN-1); the second was a ship-borne equipment having a capacity of 65 sec and identified as AN/SRQ-2 (XN-1).

Both these equipments consisted of a recording channel, a frequency indicator, a magnetic-tape recorder unit, an audio-monitor channel, a reproducing channel, means for generating a-c and d-c erase and bias currents, a modulator, a power supply, and various accessories. A block diagram is shown in Figure 1. The equipment is arranged for operation either from the 5.25-mc i-f output of an R-44/ARR-5 or similar receiver through an adapter plug or from the audio or video output of any suitable receiver through the modulator which converts such output signals into 5.25-mc modulated signals.

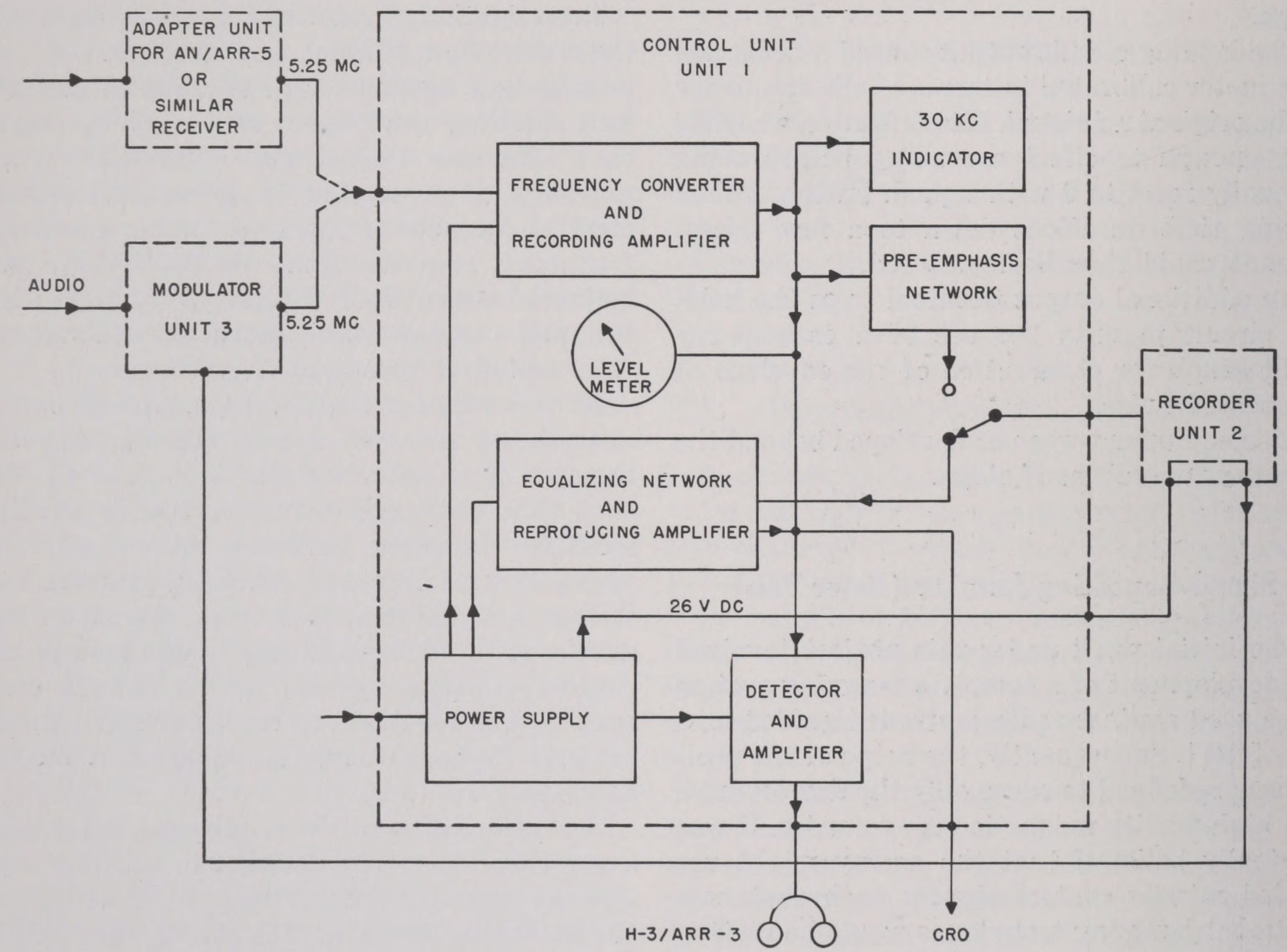


FIGURE 1. Block diagram of receiving equipment for signal-repeating jamming system.

In the recording channel, the 5.25-mc modulated signal is heterodyned to a 30-kc carrier frequency, and both the carrier and its sidebands are amplified to a level suitable for

SECRET

recording. A frequency indicator comprising an electron-ray tube and an amplifier is connected to the output of the recording channel and is arranged to produce a minimum tuning-eye indication only when the output of the recording channel is within 500 c of 30 kc. This indicator, plus a power-level meter, provided means for insuring a recording-channel output of the proper characteristics for recording.

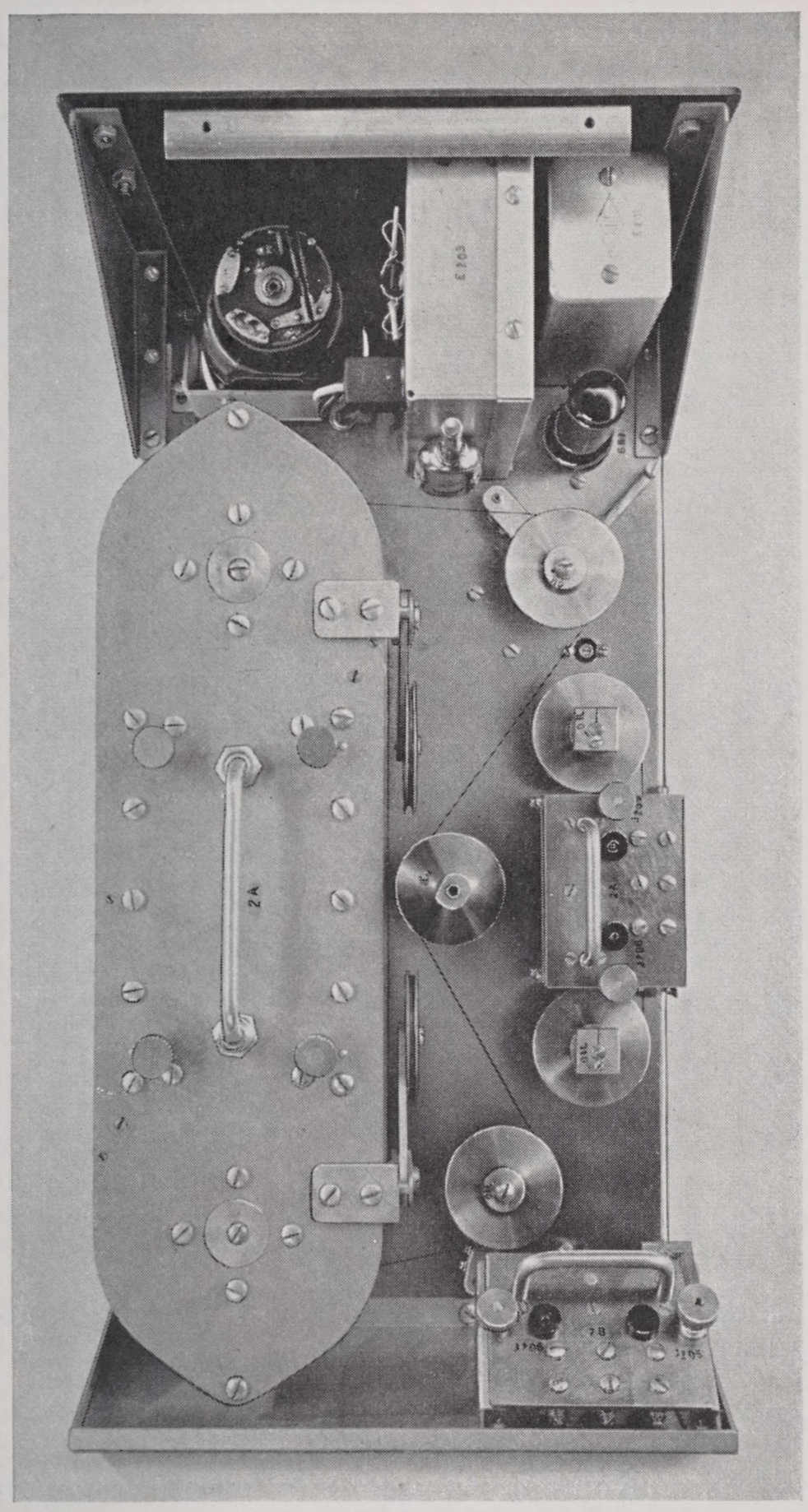


FIGURE 2. Top view of wire recorder unit of receiving equipment for signal-repeating jamming system.

The output of the recording channel is applied through a pre-emphasis network to the recording head of the recorder unit. This network is designed to provide constant-current output for input signals between 0.2 and 60 kc when terminated by the recording-head impedance.

The recorder unit to which the output of the recording channel was applied is shown in Figure 2. This unit includes a magazine capable of accommodating 122.5 ft of Vicalloy recording tape between a pair of rotatable drums. A drive mechanism is provided to carry the recording tape from the magazine through a head-plate assembly on which are mounted three pole-piece assemblies providing means, respectively, for subjecting the tape to d-c and a-c erase currents and to the signal to be recorded superimposed upon an a-c bias current. The tape-drive mechanism is arranged to carry the tape through the head-plate assembly at constant speed, irrespective of variations in motor speed occasioned by changes in supply voltage or temperature, and both the lubrication system and the lubricants used are arranged to provide freedom from temperature effects.

A single-tube oscillator included in the recorder unit provides means for generating a 160-kc a-c erase current and a 320-kc a-c bias current, the plate-tank circuit of the oscillator being tuned to 160 kc, while the cathode circuit is tuned to the second harmonic of the oscillator frequency, or 320 kc. For playback purposes, the signal generated by the passage of the magnetized tape through the recording head is applied to a reproducing channel which is designed to provide an output suitable for signal analysis either with a cathode-ray oscilloscope or with a harmonic analyzer. This channel includes a two-stage equalizer-amplifier having a response which is the inverse of that of the recorder and a cathode-follower output stage.

An audio-monitoring channel comprising a grid-leak detector and a cathode-follower output stage may be connected either to the output of the recording channel or to that of the reproducing channel. This monitoring channel may be used for search purposes or during recording and reproducing but is not intended for use in signal analysis, since its frequency-response

SECRET

and distortion characteristics are not suitable for this purpose.

The modulator, which is designed for use when the audio or video output of a receiver is to be recorded, includes an audio amplifier, a 5.25-mc crystal oscillator, and a modulator in which the locally generated 5.25-mc carrier can be 95 per cent modulated by the input signal with less than 1 per cent distortion.

The power supply for the entire equipment may be operated from any 110-v primary power source having an output frequency between 60 and 2,600 c. A voltage regulator is used and the output of a conventional full-wave rectifier is applied through a single-section RC pi-network to the regulator. This regulator comprises two parallel-connected regulator tubes, a two-stage control amplifier, and a voltage-regulator tube which provides reference voltages. Both stages of the control amplifier are operated with fixed reference voltages obtained from the voltage-regulator tube, which is connected across the regulated output rather than across the unregulated input, as is usual with the more common regulator circuits. This power supply is capable of maintaining a regulated output of 300 v direct current with a hum level of less than 10 mv.

The above-described circuits are accommodated in three units. Unit 1, the control unit, includes the recording channel, the frequency and level indicators, the reproducing channel, the audio-monitoring channel, the power supply, and the switching circuits. Unit 2, the recorder unit, includes the tape magazine and drive mechanism, the head-plate assembly with its three pole-piece assemblies, and the bias-supply oscillator. Unit 3, the modulator unit, includes the modulator used when the audio output of a receiver is to be recorded.

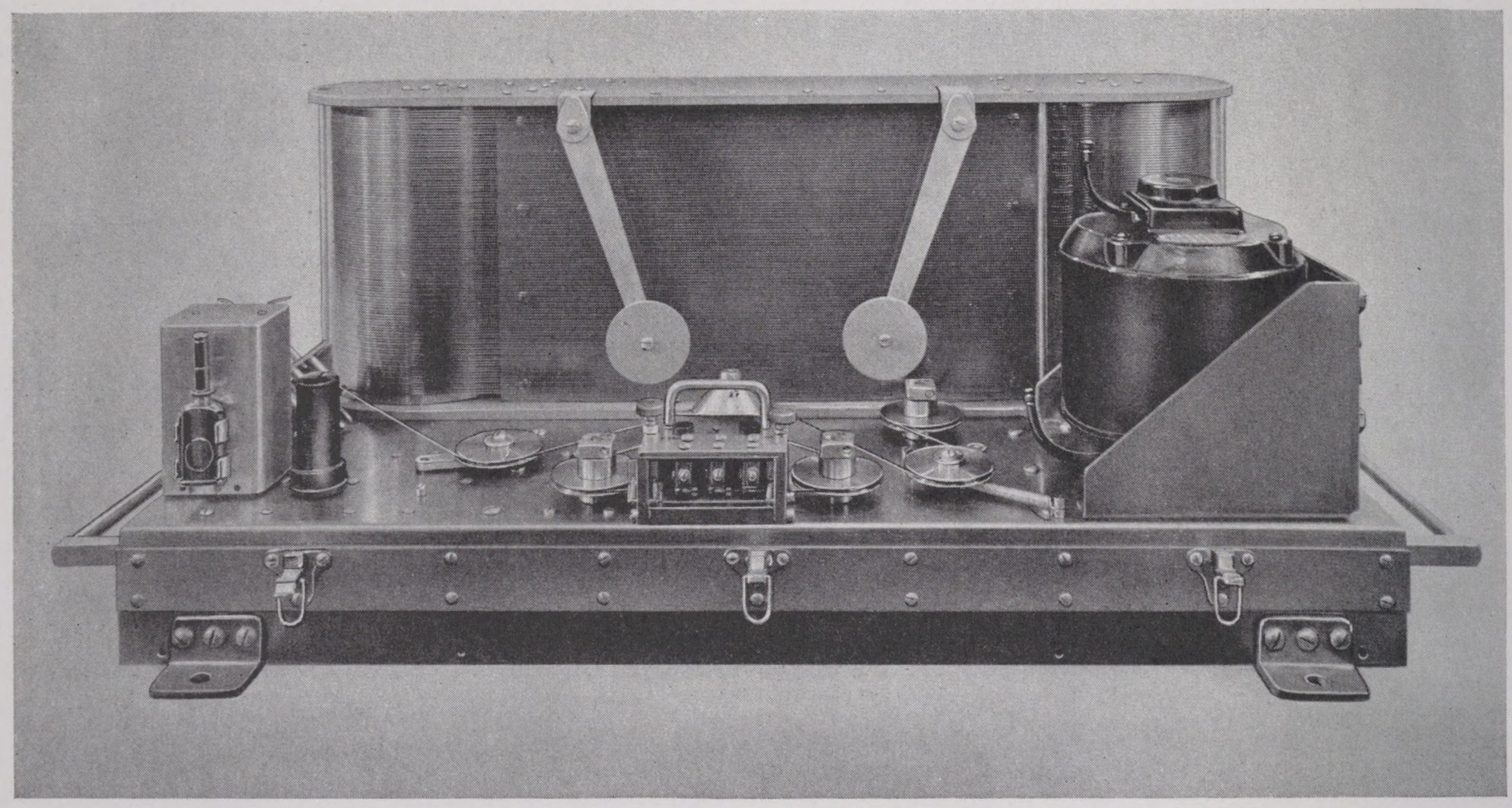


FIGURE 3. Side view of wire recorder unit of receiving equipment for signal-repeating jamming system.

AN/SRQ-2 (XN-1) EQUIPMENT

This equipment represents a modification of the previously described AN/ARQ-12 (XN-1) equipment to increase the recording time to 65 sec and to fit the equipment for ship-borne use. Thus, the AN/SRQ-2 equipment comprises a Unit 1 control unit, a Unit 3 modulator, and a 65-sec recorder unit. As shown in Figure 3, the recorder unit is generally similar to Unit 2 of AN/ARQ-12 but is of a suitable size to accommodate the required length of tape.

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ACCESSORIES

In addition to the three major units making up AN/ARQ-12 (XN-1) and AN/SRQ-2 (XN-1) equipments, several accessories were provided. One of these was an adapter plug assembly arranged to replace the diode detector of a communications receiver and to provide a plug into which the detector could be inserted. This adapter plug assembly permits the coupling of the 5.25-mc i-f output of the receiver to the input of the recording channel.

Another accessory comprised a rewind-reel assembly for use in changing tapes in the magazine. This assembly was made in two sizes, one for each of the two recorder units, and provided reels from which a fresh tape could be wound into the magazine at the same time as the used tape was removed therefrom. An additional accessory was a lap welder by means of which the ends of the recording tape could be joined to form a continuous loop.

PRODUCTION

Several AN/ARQ-12 (XN-1) and AN/SRQ-2 (XN-1) equipments were produced at Airborne Instruments Laboratory. In addition, complete specifications were prepared for the use of an outside contractor in the production of additional AN/ARQ-12 and AN/SRQ-2 equipments. Several pilot models of the AN/ARQ-12 (XN-1) and AN/SRQ-2 equipments were shipped to the United Kingdom for use in the Big Ben project.[b]

7.3.3 Search Receivers for Proximity Fuzes

This project involved the development of an improved search receiver of the panoramic type for use as a proximity fuze countermeasure. Initial requirements were coverage of a band extending from 75 to 230 mc, continuous visual presentation, high stability for airborne use, and immunity from radar barrage jamming. For a description of the receiver developed, see Chapter 10.

[b] The Big Ben project was concerned with the investigation of possible navigational aid signals for V-1 and V-2 bombs.

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Chapter 8

NONRADAR JAMMING TRANSMITTER TECHNIQUES

8.1 INTRODUCTION

A NUMBER of equipments for jamming communications and guided missiles [GM] were developed by the laboratories operating under Division 15 auspices, and a considerable amount of work was done in developing jammer techniques. At the same time, studies were made of the jamming susceptibility of various Allied and enemy equipments, most of which are discussed in Chapter 9. However, some of these studies bear such a close relation to the development of jamming equipment that they are discussed in this section.

Most of the work on the development of jamming transmitters for communications and guided missiles countermeasures was carried out by the Airborne Instruments Laboratory (under contract OEMsr-1305), the Federal Telecommunication Laboratories, Inc. (under contracts OEMsr-285 and 936), the Radio Corporation of America (under contract OEMsr-895), and the Bell Telephone Laboratories, Inc. (under contracts OEMsr-940, 993, 778, and 966). The work under these various contracts is summarized in this chapter. The research projects on jammers for use against proximity fuzes are described in Chapter 10.

8.2 GENERAL STUDIES OF COMMUNICATIONS COUNTERMEASURES

Radio communications countermeasures is a broad term which includes all the various phases of interfering with enemy communications by means of jamming, and of protecting friendly communications against jamming by the enemy. Radio communications include all means by which intelligence is transmitted by radio, that is, telephone, telegraph, direction-finding [DF] signals, etc.

Jamming refers to partial or complete obstructions of radio communications by means of radio transmissions deliberately generated to interfere with reception. Jamming interference may prevent reception by overriding (masking) communication signals, distracting the listener, disrupting the communication signals, incapacitating the receiver, or by a combination of these means. Antijamming [AJ] refers to the means and methods for reducing the effectiveness of jamming interference.

8.2.1 Basic Considerations

Jamming transmitters are distinguished, among other things, by (1) whether they are intended for use against communications or radar channels; (2) whether they are airborne, ship-borne, ground-based, or expendable; (3) whether they provide barrage or spot jamming; and (4) their effective output power.

For this reason, there is a variety of jamming transmitters, each intended for specific applications. There may even be more than one type of transmitter for a given frequency band, each differing from the others in one or more of the above respects.

Much of the following material applies equally well to radar jamming, and much of the material presented under that head in Chapter 11 applies here. Some of the transmitters, moreover, can be used for both radar and nonradar jamming. Chapter 11 (and Chapter 10) should, therefore, be consulted also in this connection.

General Jamming Problem

The effective use of jamming requires that account be taken of tactical as well as technical considerations. For example, interception of enemy communications can be of considerable value and the use of jamming must be considered in relation to the value of interception. Since jamming and interception generally cannot be carried on simultaneously, a decision must be made as to which will yield the larger benefits in any given situation. In general, lower echelon communication circuits which transmit orders requiring immediate action are good candidates for jamming, because their in-

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tercept value is low. In the higher echelons, where the communications concern larger and slower movements, interception may be of more value than jamming. Under certain conditions, jamming may be used as an aid to interception by forcing the enemy to repeat messages. In any case, jamming must be under control. Its unorganized use may convey information to the enemy, prevent desirable interception, and endanger friendly communications.

An exception to the general philosophy of limiting jamming transmissions as much as possible would be in an instance in which a false appearance of activity is to be created. If the enemy came to associate jamming operations with increased activity, it might be desirable, upon occasion, to operate jammers deliberately for deception and confusion purposes.

From a technical standpoint the jamming problem is one of disrupting enemy communications with a minimum of equipment and personnel. To jam an enemy communication signal completely requires that his receiver be bombarded with jamming energy about equal to, or greater than, the energy in his signal. The amount of jamming power required depends on the power radiated by the enemy transmitter, the location of the jammer with respect to the enemy station, the radiation characteristics of the jamming and victim systems, and other factors. The effectiveness of jamming power can be increased by concentrating it on the receiver by means of a directive antenna or by locating the jammer so as to obtain favorable propagation conditions, as in aircraft.

Scope of Activities

The broad picture given above will serve to indicate that effective jamming requires consideration of a wide variety of technical problems, including such factors as (1) propagation of radio waves (discussed in Chapter 6), (2) relative effectiveness of various types of jamming interference, (3) effect of receiver characteristics on effectiveness of jamming signals, (4) the choice between spot and barrage jamming, (5) design of jamming transmitters (see also Sections 8.3 and 8.4), (6) antenna efficiencies and directional characteristics (discussed in Chapter 4), and (7) integration of the various elements into a jamming system. Since in any jamming system it is necessary to select the channels to be jammed, there is also the related problem of searching, observing whether jamming is effective, and in some cases direction finding to locate the source of the enemy signals. The general receiver problem is dealt with in Chapter 7; but certain receivers which form integral parts of complete jamming systems are described here (Sections 8.3 and 8.4).

Theoretical analyses have been made and considerable information gathered on all these subjects by laboratory investigations and field tests. In this program, the contractors have been guided by consultation with the Armed Services and participation in various Office of Scientific Research and Development [OSRD] committee meetings, by analyses of intelligence reports which were made available, and by participation in Army maneuvers in this country involving the use of radio countermeasures [RCM]. In addition, through experienced RCM personnel supplied for service abroad for various periods, a knowledge of theater problems, conditions, and requirements has been acquired. (See Chapters 14 and 15.)

As the work progressed, individual reports on various phases of the jamming problems have been issued. This information was reviewed and the more important findings used in the preparation of Division 15 *RCM Handbook No. 4* on the jamming and antijamming of radio communications.[345] This consists of the following parts: Part I "Jamming and Anti-Jamming of Radio Communications—An Introductory Survey of Technical Considerations," Part II "Estimating the Performance of Radio Telephone Jamming Systems," and Part III "Estimating the Performance of Radio Telegraph Jamming Systems." The handbook, supplemented by other reports,[262] contains a large amount of the useful technical information at present available on the subject of communication jamming and therefore constitute basic reference material for systems studies. A large part of the background material for these reference handbooks was provided by the various reports issued under contracts OEMsr-778, 940, and 966.[59-67, 167-246] More specific refer-

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ences to many of these reports are given at the appropriate points below.

8.2.2 Types of Jamming Modulation

The type of modulation employed for jamming purposes depends upon whether a telegraph, telephone, or radar channel is being jammed, upon whether spot or barrage jamming is being employed, upon the vulnerability of the victim receiver to various types of modulation, and upon the kind of modulation that can be produced at the carrier frequency and power output of the jammer.

In the jamming of communications channels, one consideration in the choice of type of modulation is the psychological reaction of an operator to novel forms of interference. The modulation may be chosen to distract the listener rather than to obliterate the desired signal. This technique is of particular importance when the jammer lacks sufficient power to mask the victim signal, since even a weak distracting signal may succeed in preventing the reception of any great amount of intelligence. In addition to the studies reported below, many investigations of the effectiveness of various jamming signals have been made from the AJ point of view and are discussed in Chapters 9 and 13.

Audio Waveform Requirements

Under contract OEMsr-626, an investigation was made of the effectiveness of various a-f noises in masking speech and telegraphy, and the reports provide an excellent introduction to the audio requirements of jamming.[18-21] It was concluded that in the final audio circuits the interfering wave should be continuous in both frequency spectrum and time, that gaps in frequency or time should be made as small as possible, and that noises having the properties of audio-resistance noise are especially effective.[19, 21]

Radio Waveforms

With regard to the r-f output of a communications jamming transmitter, it may be said that in barrage jamming, and probably in any other kind, the ideal type of signal is the one characterized by the greatest disorder. One way of looking at the effect of the output jammer is as follows.

Any disturbance whose spectrum falls completely in a band of frequencies small in width compared with the mean frequency can be represented as

$$f(t) \cos [\omega_0 t + \phi(t)], \qquad (1)$$

where $f(t)$ represents the envelope of the amplitude, ω_0 is the mean frequency, and $\phi(t)$ is a varying phase term whose time derivative is the instantaneous angular frequency. Both f and ϕ may vary in time, in a manner related to the width of the spectrum.

Amplitude Modulation. There are two ways of introducing disorder into expression (1). Suppose first that $\phi(t)$ is held invariant with time and $f(t)$ is modulated between zero and some positive value. This is recognized as amplitude modulation and gives a spectrum consisting of a carrier plus upper and lower sidebands. It might be represented as a vector of fixed phase and changing length, having constant frequency ω_0 and phase ϕ. If $f(t)$ has a uniform spectrum up to a limiting frequency and zero above it, the double sideband will have a uniform spectrum over twice the frequency width. The carrier represents energy without disorder and would not be expected to be effective in jamming. Its power is more or less wasted, and the carrier might better be eliminated if its presence makes difficult the production of maximum sideband power.

This double-sideband type of signal with carrier eliminated—direct-noise amplification (Dina)—has been used and is a very efficient type. It may be objected that the two sidebands are not really independent, since the phase relations are such that in a vector diagram the vector would travel a straight line centered at the origin. This is true if the receiver is tuned exactly to the suppressed carrier—a situation which is hardly likely to arise in practice.

Frequency Modulation. A second method of introducing disorder is to hold $f(t)$ constant and let $\phi(t)$ or $d\phi/dt$ vary. This is phase or frequency modulation and can be made to give a uniform spectrum over an r-f band. That uniformity of spectrum does not tell the whole

story is very clear here. As a function of time $d\phi/dt$ might be made up wholly of very l-f components so proportioned as to make the r-f spectrum desirably flat; yet for jamming the result might be poor because the instantaneous frequency $d\phi/dt$ passes through the band of the receiver so infrequently that amplitude limiting of a crude type becomes a very effective AJ measure. To avoid this, it is desirable as a minimum to insure that the instantaneous frequency will sweep through each channel often enough to prevent the transient in the receiver from decaying below the level of communication signal. As an oversimplified example, if the receiver comprised a single r-f tuned mesh having a half-power bandwidth Δf equal to 5,000 c, and a time constant $1/x\Delta f$ sec, we would require about $x\Delta f$ crossings per second, so that the modulation frequency would need to be $x\Delta f/2$ to meet the condition at the middle of the barrage. Actually, it is probably preferable to provide a more rapid rate, so that transients from several sweeps coexist in the tuned circuits. The fundamental point is that the spectrum is only half of the story and that true randomness does not exist in a spectrum in which spectral components are connected by some special phase patterns, such as is required to give the envelope a constant amplitude.

Sideband Energy Distribution. A knowledge of the distribution of energy in the sidebands of a modulated jamming transmitter is essential in planning the details of tactical application of the jammer, especially in barrage jamming. This is particularly true when a number of transmitters must be used to cover the band of frequencies involved. As detailed below, the distribution of sideband energy considerably influences the manner of setting the carrier frequencies of the various transmitters involved in a barrage operation of this type. Information concerning the distribution of the sideband energy is also vital to calculations of the effectiveness of a jammer for protecting a given target against a specific radar.

Theoretically, the distribution of energy in modulation sidebands is confined to specific frequencies when recurrent waveforms are used for the modulation. Consequently, there are likely to be gaps in the spectrum. The widths of these gaps are a function of the parameters involved, and, under some circumstances, such types of modulation may be entirely unsatisfactory for the purpose.

In practice, the actual distribution of sideband energy may differ considerably from the theoretical values because of the characteristics of the electrical circuits involved. For example, there may be a considerable amount of incidental frequency modulation of the carrier. Under these circumstances, as compared to the theoretical distribution, there are relatively large amounts of energy spread over a considerable band in the vicinity of the carrier frequency. A transmitter having incidental frequency modulation of the carrier is more effective in jamming receivers close to the nominal carrier frequency than if the frequency modulation were not present. The incidental frequency modulation allows the carrier energy to be effective in jamming, even though continuous-wave [c-w] AJ devices may be in use.

Random Noise

The search for disorder leads one naturally to noise, which deserves special emphasis. Noise is random both in amplitude and in instantaneous frequency and so can be considered the acme of disorder. It has a uniform spectral distribution of energy, except as it may be influenced by the circuit elements. As the barrage bandwidth is widened, the spectrum of the envelope $f(t)$ and that of the phase term $\phi(t)$ in expression (1) will be widened in proportion. Since noise has no periodically recurring frequency, it cannot be filtered out or otherwise eliminated without also removing the desired signal. This is a description of thermal noise, which is the basic factor limiting the sensitivity of any receiver. Thermal noise, therefore, has come to be regarded as the ideal type for jamming.

Noise has another attribute that makes it a desirable type of jamming modulation. This is the fact that the presence of a noise jamming signal in a receiver may not be recognized as deliberate jamming. It is, therefore, a subtle type of jamming that may be practiced for some time, upon the uninitiated, before being

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recognized for what it is. There is, however, another factor to be considered in this respect, particularly in the jamming of communications channels. Many operators are experienced in listening through background noise and therefore have less difficulty in adjusting themselves to this form of interference than to stepped tones or some other novel form of jamming. Furthermore, an inexperienced operator is prone to stop listening when he hears peculiar interference or realizes he is being jammed. With noise jamming, not realizing he is being intentionally jammed, this operator continues to copy or try to copy. These factors are variable, however, and to some extent are transient in nature and should be considered as such.

The ideal nature of thermal noise, therefore, cannot always be accepted without reservation. Thus, in the reception of c-w telegraphy, suppose that normal reception employed a beat note of 500 c. The information for slow hand speeds would then be delivered in a narrow band about 500 c. To jam normal reception it would be best to put all the power into a similarly narrow band of resistance noise clustered around the radio carrier. Unquestionably, this would be very effective if the communication carrier frequency could be followed that accurately, but, as a practical matter, we might have to use a band of, for example, 1,000 c. It has been found, under some circumstances, that if the receiving operator turns off his beat-frequency oscillator, the telegraph signal can be read as a small but perceptible modulation of the thermal noise itself. In other words, each small band of thermal noise acts like the beating oscillator itself. In this case, it is desirable that the thermal noise be given an additional strong modulation, itself random in character, and in the same frequency range as the signal to be jammed.

A disadvantage of noise modulation, from the equipment point of view, is the possible difficulty of generating the desired amount of noise-modulation power, particularly at the higher frequencies and at the higher output levels. (See Chapter 2 on noise sources.)

Clipped Noise. When random noise is clipped at the top, the spectrum retains its continuous character but is changed in shape. When the clipping occurs at a level very low compared with the effective value before clipping, a constant amplitude exists most of the time and the waveform tends toward that of a constant amplitude which is frequency-modulated. Thus, this constant amplitude exists about 90 per cent of the time when clipping is at 30 per cent of the effective amplitude.

Underclipping, on the other hand, accentuates the pulse peaks, in some ways giving the effect of noncoherent pulses. It is apparent that this must not be carried so far as to lead to overly long silent intervals. This becomes especially important as the width of the barrage band is decreased, since the intervals of silence will then increase and may become dangerously large. Class C amplifiers produce this effect and must therefore be avoided in narrow barrages. On the other hand, Class C amplifiers may safely be used when the width of the barrage is very great compared with the band of the victim receiver.

Other Modulations

Various forms of modulation other than noise are used for jamming, particularly for special purposes. In many cases, however, other modulations are more effective than random noise even for communications jamming, as indicated above, because of power or bandwidth considerations. Some of the commoner types are as follows.

Continuous Wave. The use of an unmodulated carrier (c-w) for jamming may be effective in communications channels but will have little or no effect upon well-designed radar receivers. To be effective against telegraph channels operated by skilled personnel, the c-w jamming signal must be accurately tuned, so that the difference in frequency between the desired and undesired signals is within 2 to 10 c, and must be keyed at the same rate or slightly faster than the victim signal.

In telephone channels the intermodulation products that result from the presence of an undesired c-w carrier can also be effective in preventing the reception of intelligence. The optimum difference in frequency between the desired and the undesired carrier for maximum jamming is in the vicinity of 500 c. It is to

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be noted that, in the two types of communications channels mentioned, c-w interference is effective only in spot jamming and then only if present in sufficient strength and if accurately adjusted to the optimum relative frequency for jamming.

Sine-Wave Modulation. If the carrier is modulated by a sine wave, the jamming will sound like a pure tone in the receiver. This is a relatively ineffective form of jamming by itself and requires considerably more jamming power than noise, for instance. When the frequency of the modulation is varied, however, the effectiveness is greatly increased.[271] In some forms, the variation is in steps (Bagpipes), whereas in other transmitters it is continuous.

Noncoherent Pulses. Another special example of waveform consists of noncoherent pulses.[181] First consider an isolated rectangular pulse of radio frequency, having a duration of 1 μsec and an instantaneous frequency of 100 mc. The Fourier integral shows its spectral shape to be the familiar sin x/x shape with zeros at 99 and 101 mc. About the maximum (100 mc), the spectrum is fairly flat. In a series of these pulses at regular or irregular periods of the same or equal amplitude, the shape of the spectrum remains unchanged, provided that there is no relation between the phases of successive pulses. If there is a phase relation such that the oscillations appear to be merely sections of the same sine wave, the spectrum is altered. A large amount of energy appears in a carrier at the middle of the spectrum, and the whole spectrum may become bumpy. In particular, if there is a periodic repetition of equal pulses, such phase interdependence leads to a line spectrum instead of a band spectrum, the lines being separated by a frequency equal to the pulse frequency. The pulses are then said to be coherent in phase; without phase dependence they are called noncoherent.

This is a form of noise having much to recommend it but also having its definite limitations. Its advantages have to do with the ease of producing acceptable powers in simple and easily maintainable apparatus; its disadvantages, with the difficulty of obtaining a sufficiently high pulse rate to jam wide-band receivers. Difficulty is to be expected when the period between pulses exceeds the time constant of the receiver or is of the same order. It would be preferable to have this period considerably less than the receiver time constant.

Selection of Modulation Waveform

There are a great many factors involved in selecting the most effective waveform for the modulation of a jamming transmitter, including the characteristics of the receiver to be jammed. These factors are discussed in detail in Section 8.2.3, where references are given to reports comparing the vulnerability of various receivers and the effectiveness of various jammers. Reports are available also on the relative effectiveness, in general, of the various types of jamming signals.[61, 64, 104, 205, 213, 220, 222] Because of the growing use of limiting circuits and other devices for giving AJ protection to receivers, the selection of the best waveform in future work on jamming transmitters is a matter of increasingly great importance.

8.2.3 Effectiveness of Jamming

As is seen in Section 8.2.2, a wide variety of types of interference have been used or proposed for use, such as steady carrier, keyed carrier, and carrier which is modulated in amplitude or frequency by a single frequency, by resistance noise, by a sawtooth wave, or by a series of tones (Bagpipes). Sweep types of jamming may consist of mechanical frequency modulation, either smooth or jittered. Additional types of interference are buzzer (spark), directly amplified resistance noise, carrier-suppressed (sideband) transmission, and pulses.

Since the characteristics of various radio systems differ, some types of radio circuits are more vulnerable to a given type of jamming signal than others. Tests of jamming effectiveness therefore involve the evaluation of combinations of jammer and communication set characteristics. Such tests are best made on the actual equipment under controlled laboratory conditions. These tests should be supple-

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mented by such flight tests as are required to check the mechanical operation of the jamming equipment and to determine the radiated power in various directions when the jammer is loaded into its recommended antenna. However, it should not be necessary to make airborne jamming tests of each jammer against every known or projected enemy communications link. Instead, jamming results during airborne tests against a receiver of known characteristics can be applied to other receivers when their jamming susceptibility has been determined in the laboratory.

Vulnerability of Receivers

Through poor design, some receivers may be very vulnerable to some simple form of modulation. Since it is often possible to obtain larger power outputs and relatively simple design when simple types of modulation are employed, such shortcomings of enemy equipment should be exploited. At the same time, the ease with which these weaknesses may be corrected must also be borne in mind, since the useful life of any offensive RCM device depends upon how difficult it is to devise an antidote and put it into service. As an example of this, it is to be noted that some receivers may be made less vulnerable to simple types of jamming signals simply by manipulating the volume controls in what might be considered an abnormal manner.

Although tests may indicate that a given receiver is particularly vulnerable to a certain type of modulation, it does not necessarily follow in practice that this type is the best to use. In determining the best type, it is necessary to give consideration to the practical aspects of employing this type of modulation in an actual transmitter. For example, one type of modulation may be twice as effective as another; yet it may be possible, with a given amount of input power, to obtain four times as much output with the less desirable modulation. Under these circumstances, use of the latter may be indicated.

Tests of Jamming Effectiveness

Jamming is no exception to the general rule that progress in engineering development depends upon measurement. Methods were devised, therefore, for assessing the effectiveness of jammers of various sorts, expressing it in such terms as to facilitate analysis and make possible the intelligent statement of barrage requirements. The practice was to produce a modulated signal, to measure samples of signal and of noise separately, and to attenuate them separately to significant reception levels. The samples were then mixed and impressed on the receiver to be jammed. Obviously, good shielding was needed (see also Chapters 9 and 13).

Test Techniques and Procedures. There was little background of experience to draw on for this type of work, either from the standpoint of measuring technique or definitions of terms to be used in evaluating and comparing performance. One of the early and continuing phases of the work was the evolution of a good laboratory setup and test procedure, involving the construction of shielded rooms, special apparatus for simulating radio-transmission paths, and apparatus for producing many types of signals. Some of the more complete block diagrams of the test and shielding arrangements and discussions of test methods are given in various reports[212, 215, 232, 237] (see Chapter 5).

With respect to standardization of definitions and testing procedures, a committee cooperated in the preparation of a report[262] outlining the methods of testing jamming effectiveness in use. This report is good reference material for an understanding of the various terms used in the individual reports issued on this subject and should be of considerable value to others who may enter this field.

Some 20 different types of a-m and f-m jamming signals were used in the laboratory in evaluating jammer performance and receiver vulnerability from the standpoint of both telephone and telegraph communications. Some of these were simulated jamming signals; in other cases actual jamming apparatus was used. Tests of receiver vulnerability were made not only on American sets of the types commonly used but also on a number of captured German and Japanese radio receivers. Knowledge of the performance of American sets was needed not only for developing AJ techniques but also for determining their vulnerability relative to enemy

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sets, in order to avoid jamming our own receivers in areas where jamming is used against the enemy on a fluid front.

Results of Tests. The results of these measurements are given in many reports on the specific pieces of apparatus concerned.[a] Some of the more important general conclusions found[174] are as follows: (1) With suppressed-carrier, really carrierless (Dina) noise, jamming of a carrier with high percentage amplitude modulation occurs when the noise accepted over the speech sideband spectrum is about equal to the carrier power. (2) One source of noncoherent pulses and two f-m jammers were each 1 or 2 db less efficient in jamming a narrow-band a-m receiver than the Dina, when all of these were used so as to give noise-type interference. (3) All superregenerative receivers tried were very susceptible to Dina noise and required some 14 db less noise power per kilocycle of r-f band at the jamming point than the narrow-band receiver; for one f-m receiver this figure was 10 db. (4) One American superregenerative receiver was as easily jammed by noncoherent pulses as by Dina noise. (5) A Japanese type of superregenerative receiver which had broader band characteristics than the American was about the same in susceptibility as the narrow-band receiver when the pulse rate was sufficiently high (80,000 pulses per second).

Jamming Power Requirements

In general, it is desirable to employ as much jamming power as possible. As a practical matter, however, the weight, bulk, portability, and power drain of the equipment often determine the size of the transmitter that can be used. Furthermore, it is not economical on any score to provide jamming transmitters that are appreciably larger than necessary to accomplish the desired end.

A discussion of the exact mathematical relationships whereby the jamming power may be calculated for a specific case is beyond the scope or intent of this book, but the manner in which the various factors involved influence the jamming power requirements is outlined below. A knowledge of these relationships is of considerable value, since, if the performance of a given jammer against a given enemy system is known, an accurate estimate can thus be made as to its performance under slightly different conditions.

In the jamming of communications channels, line of sight between the jammer and the victim receiver seldom exists (as it often may in radar jamming), with the result that it is generally necessary to take into consideration the effect of the earth upon the propagation of the jamming signal. Because of the large number of parameters involved, this can be done readily only by reference to propagation curves that have been prepared for the particular values of frequency, soil conductivity, dielectric constant, and transmitter and receiver antenna height involved (see Section 6.3.2).

Other factors being equal, the power required to jam a communications channel is (1) directly proportional to the power output of the victim's transmitter, the power gain of the associated antenna, the discrimination of the receiving antenna against the jamming signal, and the jam-to-signal [J/S] ratio for the type of receiver and modulation involved; and (2) inversely proportional to the power gain of the jammer antenna in the direction of the victim's receiver.

It is evident that, in order to calculate the effectiveness of a jammer accurately, considerable information, some of it concerning the victim's equipment, must be available. It is possible under some circumstances, however, to make use of a comparison method that will often give sufficiently accurate results to be useful. This method consists of setting up a receiving site where the relative value of the victim and the jamming signal can be determined and then, from a knowledge of the location of the enemy receiver and the jammer, calculating the estimated effectiveness of the jamming. Although this method also involves the use of wave-propagation curves, it does not require so much detailed information concerning the enemy equipment.

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[a] References 65, 174, 196, 207, 211, 212, 217, 219, 221, 224, 226, 228, 229, 232, 233, 236, 255, 257-261, 263-268, 270-281, 283-287. Summaries of this type of information, including the results from some of the references listed above, are given in reference 345.

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8.2.4 Barrage versus Spot Jamming

There are two ways in which one can ensure that all the communications channels of immediate interest are jammed. The barrage-jamming method is to spread the jamming energy over a frequency band wide enough to neutralize a number of channels simultaneously, so as to be certain of blanketing the victim channels. Contrasted to this is spot jamming, in which the transmitter is tuned to exactly the same frequency as the victim signal and the jamming energy is concentrated in a frequency band just wide enough to neutralize one channel adequately. Each of these methods has advantages of its own.

Comparison between the Methods

Spot jamming requires the use of as many transmitters as there are channels to be jammed and also the attendance of skilled operating personnel. On the other hand, in jamming communications channels, the presence of an operator is usually desirable in any case for identification of the victim signals. Under some conditions, however, the enemy frequencies may be well known and well separated from friendly ones, so that continual identification is unnecessary; in such circumstances, a barrage jammer can be preset and simply switched on when the jamming is begun. Moreover, because of the broad band covered, a barrage jammer can be set less carefully to start with but has the disadvantage that it prevents the use of many channels for friendly communication, except where the jamming is done deep in enemy territory (from aircraft, for instance).

With barrage jamming, where the energy is spread over a large part of the spectrum, the interference will blanket any unused channels intervening between active ones. Although this condition prevents the enemy from reestablishing the communications by minor shifts in frequency, it is wasteful of power, so that an accurately tuned spot jammer, which concentrates its energy in the most effective way, requires less power than a barrage jammer against individual or widely spaced communications channels. When there are a large number of channels within the barrage band, however, an equally large number of spot jammers (no matter how powerful) is needed to cover them, even though a comparatively small number of barrage jammers of equal power might be sufficient. That is, in some circumstances a spot jammer can waste power by concentrating far more than is needed at a single frequency, whereas at other times the barrage jammer wastes it by spreading it too far.

The type of modulation used for spot jammers should be such that the bandwidth of the jammer exceeds that of the victim channel by an amount only sufficient to allow for inaccuracies in aligning the jammer with the victim signal and for the frequency drift of the jammer and the victim channel. Barrage jammers should be provided with a form of modulation that distributes the energy evenly over the band of frequencies that is being barraged. In general, a random type of modulation is more effective than a periodic type, since in many instances AJ measures may be taken to cope with the latter kind of interference.

Frequency Setting of Barrage Jammers

As contrasted with spot jammers, barrage jammers can usually be preset to the proper frequency band, and, in the case of airborne equipment, the attention required during a flight can thus be reduced to simply turning the equipment on and off at the proper time.

In the jamming of communications channels the procedure for setting the jammers on frequency is merely to make certain that the barrage completely covers the band of frequencies to be jammed. In large formations, however, where many jammers are available, it is important that their frequencies be *accurately* adjusted so that the maximum possible number of channels are occupied by the jammer carriers. This may be done by carefully spacing the *carriers* uniformly across the band occupied by the enemy systems. Under these circumstances the carriers, particularly if they have incidental frequency modulation, contribute greatly to the jamming effectiveness. In an operation of this kind, the absolute accuracy of the frequency meter used for setting the carrier frequencies need not be very great, since only the relative accuracy is im-

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portant, particularly if it is possible to check all transmitters against the same frequency meter.

Frequency Setting of Spot Jammers

If the jammers are otherwise in good operating condition, the success of any plan of jammer activity depends entirely upon the accuracy with which the transmitters are adjusted to the victim frequency. In the manually adjusted transmitters used for spot jamming, therefore, means must be provided for determining the victim frequency and for accurately adjusting the jammer to this frequency. An operator trained to identify the intended victim signals and to adjust the jamming transmitter is also required.

In spot jamming, the jammer carrier must be set as closely as possible to the frequency of the victim signal. In ground-based or ship-borne equipment this does not present a serious problem since ample equipment and operating personnel can generally be made available. In airborne installations, on the other hand, the need for conserving weight and personnel makes it desirable to preset the jammer to the proper frequency on the ground before take-off. Unfortunately this cannot be done to spot jammers, because of the setting accuracy that is required. Deviations introduced by receiver or frequency meter calibration inaccuracies, by reading and resetting errors, and by frequency drifts in both the frequency meter and the transmitter because of changes in temperature, pressure, humidity, and power-supply voltages, all combine to make it impractical to preset spot jammers. The accuracy required depends upon the type of jamming used and ranges from a few cycles per second in keyed c-w jamming to 0.5 mc or so in radar jamming. Overall accuracies of 0.1 per cent or considerably better are evidently necessary.

Even though it may not be feasible to preset an airborne spot jammer, the equipment should be adjusted before take-off as closely as possible to the frequency to be jammed. To make a major frequency change in the air is generally difficult and time-consuming. Furthermore, by setting up the equipment as nearly as possible to the desired frequency, the performance of the set can be accurately checked at approximately the frequency at which it will be used.

The accuracy of setting required for spot jamming necessitates the use of a "setting-on" receiver, which thus becomes an essential part of the jamming system. This is especially true for automatic-search and lock-on systems, in which the receiver is automatically swept in frequency until a signal is picked up, whereupon the jamming transmitter is switched on and tuned to the frequency indicated by the receiver; in this way, the need for a special operator is eliminated. Such receivers, which are integral parts of jamming systems, are described in the succeeding sections of this chapter rather than in Chapter 7, where the general receiver problem is discussed.

8.2.5 Design of Jamming Transmitters

In the following paragraphs are discussed general methods and techniques in the design and development of jamming transmitters. Details on specific jammers and associated equipment are given in Sections 8.3 and 8.4.

Frequency-Modulation Methods

A number of different systems for producing frequency modulation were considered and tried experimentally. In most cases, the aim was to produce a random modulation of some sort, generally by noise from an external source (see Chapter 2). Both electronic and electromechanical methods were developed, as well as an unusual ferromagnetic system.

Frequency-Modulation Jamming Produced Electronically. A frequency-modulation jammer was developed in which the method of modulation was electronic.[169] Reactance tubes were used to produce the modulation, the modulating signal being random noise derived from a gas-tube noise source (Gaston). Modulation was followed by harmonic generation and amplification to 100 or 200 w. This method of operation was considered for many applications.

The simplest apparatus of this kind would consist of a power oscillator which fed an antenna directly. For the purpose of design, the volt-amperes required in reactance tubes

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must be known. These reactive volt-amperes are of the same order as the power dissipation required in the reactance tubes, provided that the frequency modulation is linear. Then if the oscillator tube provides a constant rms a-c voltage e across the main condenser, the reactive volt-amperes to be provided electronically are $2e^2C\Delta\omega$, independent of the mean frequency ω. Assume, for example, two similar tubes in parallel, one as an oscillator and the other as a reactor. A 10-kw tube might have a total capacity C (both tubes and circuits) of the order of 100 $\mu\mu$f, and e might be 6,000 v; substituting these values in the equation $2e^2C\Delta\omega = 10$ kw then gives a Δf of approximately 220 kc. This crude estimate indicates that wide barrages require reactance tubes of very high ratings if the frequency is to be modulated in the final stage. A promising "switching" method[581] which was investigated seems to warrant further research.

Electromechanical Frequency-Modulation Jammers. Another frequency-modulation method which has some interest is based on electromechanical frequency variation. This was accomplished by the use of a condenser whose capacitance could be made to follow the rapid and irregular changes of random a-f noise, through the use of a diaphragm driven by a loudspeaker mechanism. The condenser thus formed is used as one of the tuning elements of an oscillator, so that the signal produced varies in frequency at random rates and amounts from the mean or carrier frequency. This type of interference was highly effective against a-m receivers, at least against those not utilizing limiters. Powers of 300 to 500 w at a bandwidth of 2 mc in the range from 20 to 37 mc were obtained under laboratory conditions. Considerable development would have been needed to perfect the special electromechanical device used, because voltage breakdown was encountered in pushing the frequency swing to the extremes required in barrage work. Nevertheless, the method might prove to have a natural adaptability where relatively narrow bands suffice.[168]

Frequency Modulation. In the course of research on expendable jammers (see below), a method of frequency modulation was developed which is thought to have applications elsewhere.[176] The method depends on the change of inductance of a coil with a Permalloy core when the magnetization is varied. In order to overcome the low Q of the Permalloy coil, positive feedback was used around two stages of amplification instead of the usual single stage. As a result, large changes of frequency could be effected merely by varying the core magnetization, which required a relatively small amount of modulating power. A second advantage was the absence of the critical 90-degree phase circuits which are needed in most f-m systems. A unit capable of producing 10 w of radio noise power was built and tested. Expendable transmitters using this system, whether for jamming or other purposes, might advantageously use the expendable sea-water primary battery recently developed.

Amplitude-Modulation Methods

As in the case of frequency modulation, various systems were developed for producing r-f signals amplitude-modulated by noise or other modulations more or less random in nature. Many of the circuits used were quite conventional, but a few of the less conventional methods employed are discussed below.

Direct-Noise Amplification. A novel form of a carrier-suppressed (really carrierless) emission is employed in the Dina type of transmitter. In its basic form this transmitter consists of a direct-noise amplifier (whence the name Dina) connected to a source of noise and designed to amplify in the r-f range in which transmissions are desired. Noise components at the desired frequency are thus amplified until they have sufficient power to be radiated. Consequently, there is no carrier and all the available output capacity of the transmitter is made available in sideband energy. This decreases by a considerable factor the output power required.[167, 178]

In the design of Dina transmitters, difficulties arise from the necessity of tuning the wide-band amplifiers to choose the frequency band. Greater flexibility and overall simplicity may be achieved by generating the noise energy in a fixed frequency band and heterodyning to the desired transmission frequency. This

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method has the added advantage that it makes possible the use of the output of the noise source in the frequency range where it is most efficient. Another method is to generate noise between the limit of zero frequency and a higher limit, modulating thereby the output of an r-f oscillator, and then suppressing the carrier but amplifying the double sidebands to the level required.

Noncoherent Pulses as a Noise Source. The idea of a noise source using short pulses with phase independent of the preceding pulse was taken up at an early stage of the work as having considerable promise. Its simplest form might consist of a self-quenched electronic oscillator in which the time between bursts of oscillation is long enough to permit the amplitude of the preceding pulse to die down below the background of thermal noise before the next pulse starts. The pulse which follows then grows from the thermal noise in the circuit, which provides the "seed" necessary for the superregenerative growth of the oscillations, so that successive pulses possess randomness of phase.

Theoretical considerations verify the experimental fact that, when used against a receiver having a narrow band, noncoherent pulses are substantially as effective for a given power as thermal-type noise. But for this to be true, the time between pulses must be small compared with the time constant of the receiver. As the time between pulses is decreased, one eventually finds that the oscillation no longer disappears in the background noise; the seed for a pulse is then not noise but the remains of the preceding pulse, and coherence of phase results. The shape of the spectrum is no longer smooth but consists of sharp peaks separated by an amount equal to the pulse-repetition rate; in the valleys between these peaks the victim station might escape. Hence wide-band receivers are favored if the pulse rate is too slow, whereas, if it is so fast as to cause coherence, narrow-band stations may be unaffected.

Thus at the outset of a project in which noncoherent pulses are to be used one needs to know, among other things, the barrage bandwidth and the receiver bandwidth, for these are related to the pulse rate needed. The orders of magnitude are *roughly* indicated by the equation:

$$\frac{1}{\text{Pulse rate}} = \frac{1}{\text{Barrage band}} + \frac{1/x}{\text{Receiver band}} \qquad (2)$$

where x is a function of the pulse length and randomness in phase and is determined by an examination of the output spectrum, which has a sin x/x shape. The value of x is not affected by the pulse-repetition frequency [prf]. The minimum pulse rate is thus implicit in the barrage and receiver bands. To meet in addition the requirement of noncoherence requires that in the decay period the residual oscillation must attenuate from full pulse power to something that is lost in the background noise.[177]

Spark Sets as Jammers. In the survey of diverse types of apparatus which might be used for causing interference, it is not surprising that a besetting sin of the earliest means of radio communication—the spark—was seized upon as a possible virtue for RCM purposes. The spark offers a natural tendency toward wide bands, to the extent that much of the difficulty of the earlier radio development arose in obtaining low decrement or narrow bands. The circuits concerned are relatively simple, and large powers had already been achieved, of course, in the old days of the spark. It was apparent, however, that much effort would be needed to develop a spark gap suitable to the high frequencies of greatest interest and capable of producing the large number of sparks which are needed, both to give the wide bands required and to nullify the AJ effects of limiting.

A theoretical study[170] of the spark when used for these purposes showed that the spectrum produced is related in a simple manner to the transfer admittance of the filter making up the discharge circuit, and that acceptable efficiencies might be expected, at least at the lower frequencies. These theoretical conclusions were encouraging.

A laboratory study[172] was made, therefore, to determine the interference value of sparks for barrage work.[104, 215] It appears that sparks are feasible for jamming and are better suited

SECRET

to barrage than to spot jamming. The r-f noise power which can be expected with the techniques considered is of the order of 50 w in the German tank band (near 30 mc), but for frequencies which are significantly higher sparks have little promise. Their most natural range would be below 5 mc, where wide bands and powers of many kilowatts seem reasonable. Unfortunately, this is not the frequency range where high-power barrages are likely to be desired. The special case of the expendable jammer is an exception.[179, 180]

Generally speaking, the considerable special development work of an electrical and mechanical nature which would be required for most projects and the high state of development of electronic equipment tended to discourage the thought that sparks have a special advantage. It is, however, a means which should not be completely overlooked.

Expendable Jammers

The use of parachute-borne, expendable jammers that can be dropped in the immediate vicinity of the receivers to be jammed offers interesting possibilities. Expendable jammers may be of several types, such as parachute-borne (to jam during the period of descent), grounded (to jam from the ground), and floating (to screen small boats, etc.). In general, jammers of this type will not be effective against systems having highly directive antennas unless the jammers are directly in the beams of the antennas. Thus, in the case of radar, expendable jammers are of doubtful value because of the difficulty, if not impossibility, of keeping them in the radar beam. In the communications field, on the other hand, expendable jammers have possibilities, since highly directional antennas are seldom used for the services under consideration. Here, as in all other cases where the merits of various types of jammers to accomplish a given end are being weighed, consideration must be given to the weight, bulk, life, and effectiveness of the various devices that are available.

During the summer of 1943, the development of expendable jammers (Chicks) was undertaken along lines related to work already well under way at Signal Corps and Canadian Service laboratories. Duplication was avoided, but the possibilities of the general method whereby large numbers of small expendable jammers would be sown near enemy receivers were considered of great importance, as was expressed by representatives of the Armed Services at liaison meetings.

Ideas as to a number of devices were current, all of which had in common the possibility that they would be used but once and that by some means they would be planted near enough to important radio receiving points of the enemy to disrupt reception in spite of the fact that the power could not be great. This would, in general, permit our own use of the same frequency range, because only a very limited geographical area would be affected. Various methods of planting were considered, including shooting in shells and free fall or parachute drop from aircraft. Work was actually undertaken to develop apparatus in which parachutes would soften the fall and in which the antenna would be designed for dropping in jungles. The frequencies from 1 to 7 mc were to be covered by the first models.[199, 209, 555]

Conversion of Communication Transmitters into Jammers

It is often possible, with relatively little effort, to convert an existing radiotelephone transmitter into a jammer by the simple expedient of providing suitable modulation. This expedient may prove to be a quick method of obtaining jammers where standard equipment is available that has sufficient output power to be effective and covers all or even a part of an enemy communications band.

There are two simple methods of obtaining a satisfactory signal for modulating the transmitter. One is to place the regular microphone in a noisy location, such as an engine nacelle (the British call this Tinsel). A second method is to make use of receiver noise by connecting the output of a convenient receiver to the microphone input terminals on the transmitter and adjusting the modulation controls for a maximum amount of sideband energy. This type of improvisation results in a spot jammer, since the width of the sidebands in a transmitter of this type is generally limited. Under these

circumstances it is essential that the transmitter carrier be set as close as possible to that of the victim.

Studies of Specific Jamming Systems

It is sometimes practical to use automatic devices that seek the victim signal, accurately align the jammer to its frequency, and then periodically monitor the enemy transmissions in order to terminate the jamming as soon as the enemy no longer uses the channel that is being jammed. Because of the feature of listening through one's own jamming, these devices are sometimes called listening-through systems.

It should be borne in mind that there is a simple counter-countermeasure for any listening-through device that stops jamming and moves on to the next signal as soon as the victim signal disappears. The victim station would only have to interrupt his transmissions long enough for the jammer to note its absence and to cease jamming. It would then be possible to make use of the equipment that had been jammed, at least until the jammer again returned to its frequency. From the point of view of the jammers, difficulty on this score can be obviated by jamming any signal for a predetermined period of time without listening through.

The development of the most effective jamming system to meet a given set of circumstances requires a knowledge of the characteristics of our own and enemy communication equipment in the frequency range of interest, the type of antennas and polarization used by the enemy, the type of terrain involved, and radio-propagation characteristics. Although the detailed steps in a given study will depend on the type of enemy radio link to be jammed, the frequencies involved, the tactical situation, the availability of jamming equipment, etc., each specific problem should be approached from a systems viewpoint, in order that proper allowance be made for all factors involved and the best jamming equipment selected for the job.

This procedure is described elsewhere.[345] Its application to a few specific problems is well illustrated in the several studies mentioned below. Although the solutions given in these reports apply to the specific conditions imposed, much of the material is of general use. Naturally, the development of better equipment as time goes on will result in a different solution to the same type of problem, but the reports illustrate a method of attack which should be useful to others confronted with similar problems in the future.

One of these reports[214] deals with an airborne spot-jamming system study, made at the request of the Air Communications Officer, which led to recommendations for a system to jam German day-fighter communications, in an effort to block coordinated attacks by enemy fighter groups on our bomber formations.

Another of these reports[223] deals with studies relating to an airborne barrage-jamming system for use in jamming: (1) ground-to-ground communications (as exemplified by the German tank circuits operating in the 27.2- to 33.4-mc band), with the jamming to be carried out by a limited number of specially equipped planes; and (2) ground-to-air communications, as exemplified by the German ground-controlled-interception [GCI] system operating in the 38.4- to 42.3-mc band, where the jamming was to be carried out by equipment carried in planes on bombing missions.

An earlier study was made of spot jamming, as applied by equipment in bombers, against German ground-to-air communications.[206] Another study of a different sort relates to the use of expendable jammers of the spark type dropped from planes to jam radio communication in a given area.[209]

8.3 COMMUNICATIONS JAMMERS AND ASSOCIATED EQUIPMENT

In this section, the various communications jammers and jamming systems developed under Division 15 are described briefly, together with associated devices such as amplifiers. More detailed descriptions of the equipments can be found in the various reports given as references for each piece of apparatus discussed, and a history of the development can be obtained, if desired, from the series of Division 15 progress reports.

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8.3.1 Barrage Jammers and Amplifiers

It should be noted here that the l-f Dina transmitter, which with its associated receiver (Dinamate) forms the AN/ARQ-8 jamming system, was developed originally as a communications barrage jammer.[367] Its chief applications, however, were as a countermeasure to guided missiles and the Japanese 80-mc gun-laying [GL] radar; it is therefore discussed in Section 8.4 and in Chapter 11 rather than here. A lightweight transmitter of the Dina type was also developed but was never put into production.

Noncoherent Pulse Jammer AN/ART-2 (Pad)

The AN/ART-2 transmitter was developed in response to a Service request for a communications jammer to be flown in carrier-based fighter aircraft, primarily to jam "walkie-talkies." The requirements on the apparatus were finally established as follows: (1) The total weight of the installation was to be less than 40 lb. (2) The d-c power requirement was to be less than 600 w. (3) The jammer had to be capable of being preset on the ground, so that the only attention required in the air was to turn it on. (4) The modulation was to be noise-type, with a bandwidth between ¼ and ½ mc. (5) The frequency range was to be from 21 to 50 mc. (6) The antenna to be used was the existing 10-mc communications antenna.[173]

Noncoherent pulses were chosen as the modulation which seemed most satisfactory, in general, against narrow-band receivers (where the jamming efficiency of this type of modulation is about equal to that of noise). In the form of modulation finally used in ART-2 (Pad), the randomness between successive pulses was confined to their relative phase, for the shapes and instantaneous frequencies were repeated. But randomness in phase alone is sufficient to give a spectrum having roughly the sin x/x shape, with no characteristic associated with the prf. An artificially high background noise was provided by means of shot noise from a phototube,[175] and an amplifier following the oscillator was used for the sake of increased power and stability, and for assuring noncoherence (randomly phased pulses).

The pulse rate used in Pad was 80 kc, and a barrage band of 400 kc was covered. If these figures are substituted in equation (2), one finds that the receiver bandwidth required to satisfy the equation is 32 kc. This figure means that Pad would be most effective against a receiver whose bandwidth is about this value; these data were not available during the development of the jammer. Later tests showed that the Japanese walkie-talkie receivers had broad-band characteristics which required an increase in the pulse rate and duty cycle of Pad.

At about this point the decision had to be made between the self-quenched and the separately quenched oscillator. Pad used self-quenching. The principles of the self-quenched type of oscillator are set forth in a report[177] which also goes into the details of the circuit design of Pad.[308] Effectiveness tests[217] and flight tests of the ART-2 showed that it met satisfactorily the requirement that it jam a Japanese walkie-talkie link 0.4 mile long from a distance of 25 miles at 14,000 ft in altitude. It was realized, however, that the pulser is actually inferior to resistance noise. On theoretical grounds, it was believed that two or more Pads would have a far greater jamming efficiency than a single one, an idea which was borne out by laboratory and Navy flight tests. Consequently, when Pads were staggered every quarter megacycle, in accordance with the original Navy plan, the overlapping of the spectra gave enough improvement that the resulting signal was not much inferior to random noise in jamming efficiency.[181]

Expendable Jammer (Chick)

Reference has already been made (Section 8.2.5) to the idea of using expendable jammers against communications networks. The National Defense Research Committee [NDRC] work on this project took the form of providing a Chick in which the interference was produced electronically, instead of by a spark, as was the case with the original models.[176] A number of different shapes for the jammers were considered. Greatest attention was given to the bomb-shaped Chick,[180] but designs were

[redacted]

drawn up and experiments made with radically different shapes.[179]

The problem of securing adequate radiation obviously was difficult. A Chick designed in Canada comprised a bomb-shaped device with fins, intended for dropping on cleared ground. A spring device was actuated when the nose struck the ground and the automobile-type antenna (drawn out by the supporting parachute during launching) was swung perpendicular to the length of the container; at the same time, two lateral legs spread away from the case to form with it a three-legged support. The United States devices were for use in jungles where a long wire—say 100 ft long—would find support in trees. Neither of these antennas was likely to be dependably effective and could be very inefficient.

A jamming analysis of Chick problems was made,[209] and a study of the optimum size for such jammers was carried out.[199] A final United States Chick model was developed and tested[180] (including flight tests), and its performance analyzed.[215] Tests were made also on the earlier United States and Canadian versions.[194] Chicks were dropped successfully from airplanes going at speeds up to 300 mph, and in most cases were found to be in operating condition after landing on bare ground. Noise fields from 100 to 200 μv per meter were produced at ¼ mile with the antenna directly on the ground. The jamming signal emitted was the equivalent of random noise; for the device was, in fact, a gas-tube noise source with several stages of r-f amplification. With this type of noise, amplitude limiters in the receiver do not constitute an AJ means as they do for simple spark-type jammers. The Chick bandwidth was such that 10 or 12 units, each adjusted to a different frequency, would be required to cover the range of frequencies from 1 to 7 mc. To jam telegraphy over this frequency range might require dropping a very large number of units.

Converted Communications Transmitters

Since there already existed a wide variety of ground and airborne radio communication transmitters when the RCM program was begun, steps were taken early in the program to adapt some of these for jamming purposes. As an example of this practical approach, one of the first procedures suggested for immediate application was that of increasing the gain of a spare receiver until sufficient thermal noise was obtained to modulate properly a communication transmitter, whose radio frequency could then be adjusted to spot-jam any given enemy frequency in the operating band of the transmitter. Another source of noise modulation used in jamming was the output from a microphone placed in the engine nacelle of an aircraft. Later, a gas-tube noise generator (Gaston) was developed, and improvements were made on this early design.

Studies were made of the modifications required to convert standard communications transmitters for use as jammers with noise sources such as Gaston or other types of external sources.[60] These modifications were carried out in the laboratory on the Navy GO-9 c-w transmitters[189, 203] and on the i-f units from them;[216] and prototypes were furnished the Armed Services. Similarly, modifications of the SCR-808 set were made to provide a stopgap airborne spot jammer which could be used against German tank and parachute troop frequencies,[197] and later an SCR-828 was modified and given flight tests.[221]

The 15-kw Ground Jammer (Cigar)

The 15-kw ground Cigar was a high-power ground jammer originally intended for jamming the German ground-to-air communications link used in controlling night-fighters. It consisted of a Lecher-line oscillator using two triode tubes (Type 889R) cooled by forced air.[300, 301] The frequency was mechanically swept through a range of about 4 mc around a mean frequency which is adjustable between 30 and 50 mc.

Various modifications were made in this equipment. A filter was designed to suppress harmonics of the radio frequency, to avoid interference to friendly communications channels in the 100- to 150-mc range.[182] A different type of audio modulation was developed to make existing Cigars useful in a related application; modification kits were manufactured and installed in the dozen or so units in service.[183]

Another modification desired was to convert the Cigar to a more efficient type of oscillation, preferably a random type of noise. Two methods of operation partially meeting the request were developed.[184] The first of these used noncoherent pulses which were self-quenched, as in Pad, and gave a power of 2 to 3 kw over an 0.7-mc band, at 40-mc mid-band. The second method was a separately quenched system of grid modulation, driven by the amplified video-frequency output of a gas tube; it gave 12 kw over an 0.5-mc band at 40 mc. This power was considerable, and the bandwidth was one of interest. The full capabilities were not realized, since this particular job was discontinued before completion on account of the general war situation.

In the course of this latter development, a number of experiments were made on separate quenching which give some information on the peculiar impedance that an oscillator presents to the triggering input circuit. These peculiarities arise from the fact that in a power oscillator the triggering terminal in general carries considerable current—for example, grid current. As the bias voltage becomes less negative and passes the point where oscillations start, a discontinuity occurs, and another appears at the stopping of oscillation. The input conditions are thus nonlinear in nature and require considerable driving power. The necessary decay of oscillation can be helped by using a gated-damper tube, which operates during the silent interval like a damper in a piano. Alternately, the amount of background noise can be raised by using a noise amplifier between the noise source and the oscillator, as was done in an English jammer.

Power Amplifier for Jammers

The AM-66/AR-XR was developed as an airborne power amplifier for jammers in the 14- to 55-mc range. As a preliminary to the development work, a considerable amount of general research was carried out on the best design for such an amplifier.[185] The AM-66 was designed to step up the output of such jammers as the AN/ARQ-1 and the AN/ARQ-8 (5 to 25 w) to about 500 w. This mid-band power was achieved for all frequency settings within the range with a half-power bandwidth of 2 mc. Several prototype equipments were built, and full laboratory and flight tests were performed, as well as tests of ruggedness.[235]

8.3.2 Spot Jammers and Jamming Systems

The following spot jammers and spot-jamming systems were developed in Division 15.

Spot Jammer for 15 to 30 mc

A research program was initiated to develop a spot-jamming system covering the frequencies between 15 and 30 mc. The final development model was used as a prototype for the Army SCR-591 and the Navy AN/ARQ-10 jammers.

Development Program. The development program undertaken was based on four general requirements for a spot-jamming system: (1) means for interception and identification of an enemy signal, (2) means for supervision of the enemy transmission, (3) means for setting the transmitter, and (4) means for modulating the carrier to give the most effective signal. The development, therefore, took shape as follows:

1. The equipment was to include a receiving system capable of spotting and recognizing the transmission of the enemy anywhere within a band and of measuring the frequency of the transmission intercepted. This was accomplished by a scanning receiver, which used a rotating condenser in parallel with the main tuning condenser. The frequency band covered by the scanning process was roughly 5 per cent either side of the mid-frequency. The frequency band covered by the equipment itself extended from 15 to 30 mc in three sub-bands.

2. Means had to be provided for observing the enemy's transmission during jamming in order to know whether the jamming was on frequency and to follow as quickly as possible any frequency change of the enemy's transmission. For this purpose, the jamming transmitter was interrupted at a rate of ten times per second in synchronism with the scanning operation in the receiver. Half of the time, the

transmitter was on, half of the time off. During the off periods, the enemy signal could be observed on the screen of a cathode-ray tube.

3. Setting the jamming transmitter rapidly and accurately to the same frequency as the enemy transmission, as seen on the receiving oscillograph, is most important, so that jamming can be started quickly and efficient use of the jamming power insured. This result was achieved by using a transmitter which was simply a self-excited oscillator, the main tuning of the transmitter being ganged with the receiver tuning. Additional trimmer tuning of the transmitter allowed accurate frequency setting. During the first part of the development, it was discovered that the method of superimposing the transmitter signal and the signal received from the enemy as seen on the cathode-ray tube did not give sufficient accuracy of tuning. In order to improve this condition, a special tuning position was provided during which scanning was removed and the cathode-ray tube used in a manner similar to a peak voltmeter. This method in itself was not entirely satisfactory; in further developments for the Navy it was discarded in favor of a very accurate counting method.

4. The carrier had to be modulated in such a manner as to render the jamming most effective, i.e., to realize the best possible masking effect for a given power (see Section 8.2.2 and Chapter 9). In this development simple means were used, the most successful one being a sawtooth modulation of variable pitch. The audio frequency was continuously changed at random within a range of ±800 c around an average frequency of approximately 1,000 c. Furthermore, in order to jam f-m communications efficiently, a mechanical frequency wobbler was provided.

Results Obtained. The equipment built was a laboratory model[15, 16, 17] of an airborne jammer, which was tested in July 1942 during maneuvers in Louisiana. The tests were extraordinarily successful, with one single jammer disrupting the communications of an entire division. These test results were largely responsible for the great effort in communications countermeasures which was started thereafter. The Army requested 50 sets identical to the prototype except for some variations in frequency band; the revised model was known as the SCR-591. These sets were built and delivered, after a relatively long delay due to the necessity of redesigning for production.

The experience gained during this development can be summarized as follows. (1) By far the most important question for efficient jamming is accurate tuning on the enemy frequency. (2) If look-through features and identification and control of the enemy are desired, a spot-frequency jammer is a complex piece of equipment. (3) The difficulty of visualizing the exact tactical use of such equipments necessitates a very broad frequency coverage, which in turn still further complicates the equipment. (4) If provision for jamming telegraphy is required, the accuracy in frequency tuning has to be extreme (within a few cycles per second). These conclusions were embodied in the Navy equipment AN/ARQ-10, which was developed on the basis of the laboratory model described above. A 500-w airborne amplifier for the ARQ-10 was designed also,[311] the AN/ARA-13, which covered from 1.3 to 42 mc in two steps: the AM-80/ARA-13 went from 1.3 to 11 mc, and the AM-96/ARA-13 from 11 to 42 mc.

Listening-Through Systems

A study was made of problems of listening through radio jamming. The technique gained during earlier work was expanded and used in the development of broad-band (18 to 80 mc) and narrow-band (±15 to 100 kc) scanners for use with radio receivers covering the frequency range 1.8 to 80 mc. These scanners and receivers were used in radio sets AN/ARQ-9 and SCR-596-T-2, which were spot jammers developed under direct Army contracts.

An important part of the work was consultation and advice on numerous other NDRC and Service projects involving r-f scanning in connection with either searching for or jamming communications signals.

Summary. Two general types of radio receivers were required for spot jamming. A broad-band scanning receiver was used in locating enemy signals and observing their frequency shifts during evasive tactics. A narrow-band receiver combining aural and visual

SECRET

indication was used to identify signals and to align jamming and victim frequencies. Synchronous control of the jamming transmitter and both types of receivers was necessary in order that the receivers might listen through during brief pauses in the jamming signal.

The broad-band scanning technique developed was used when broad r-f bands were to be scanned during intervals too short for the victim to pass effective intelligence, such as 1/30 sec. This work led to the 18- to 80-mc scanner in AN/ARQ-9, but the principles are also applicable to other frequency ranges. The development problems were more severe than those of communication receivers because of the wide range of input levels encountered and because normal AVC and r-f preselection was not feasible.[246] Among the problems for which typical solutions were found were the questions of design objectives and the choice of receiving circuits, the choice of local oscillator and intermediate frequencies to minimize spurious responses, and the synchronization of a mechanical-scanning oscillator with an electronic jam-scan cycle and narrow-band scan.

The narrow-band receiver technique involved aural receptions with a narrow-band scanner connected to the i-f amplifier to afford visual observation of radio signals at frequencies near the one to which the receiver is tuned. Special consideration was required not only for the scanning circuits but also for the r-f and i-f circuits common to both aural and visual reception. The problems considered[246] included the following: the choice of oscillator and intermediate frequencies and their effects on spurious aural or visual responses; desirable gain distribution and overload capacities throughout the receiver; the achievement of a gang-tuned r-f band-pass input selectivity, adequate for the scanning bandwidth, with regard to the usual tuned circuit selectivity; and the limitations of typical circuits.

A preliminary design for an airborne multiple spot-jamming system was developed.[245] In this system up to four AN/ARQ-9 radio transmitters could be operated simultaneously in the same airplane in order to jam an equal number of communication channels. Both narrow- and broad-band monitoring facilities were included. Synchronous control of all transmitters and of the frequency scanners was provided as an aid to the observation of victim signals. An operations plan for this system was worked out.[223]

Further Work. Many problems in connection with listening through and associated narrow- and wide-band scanning receivers remain to be solved before the relative merits of different types of systems can be evaluated with ease or their performance predicted for all frequency bands. The importance of obtaining general solutions is contingent on operational requirements and may depend in part on common interest with other uses such as communications searching and monitoring. Careful study and reporting of the performance of equipment designed for specific uses and of effects when used under abnormally severe conditions would do much to indicate which problems are most pressing.

Some of these problems are listed here without any attempt to evaluate their relative importance: (1) Comparison of the merits of broad-band scanners having synchronously swept r-f selection with those having broad-band r-f selectivity where only the heterodyne oscillator frequency is shifted at the scanning rate. (2) Study of frequency converters and methods of coupling to heterodyne oscillators, without excessive noise penalty and with a minimum number of spurious responses in covering wide frequency ranges and signal-level differences. (3) Improved synchronization of electronic and mechanical scanning. (4) Improvement of mechanically swept oscillators by reducing the retrace time. (5) Electronic control of f-m oscillators for use at higher frequencies with larger percentage swings. (6) Means for preventing a jammer in one airplane from interfering with a broad-band scanner in an adjacent airplane which is operating in the same frequency band. (7) Means for reducing radar interference in scanning receivers. (8) Use of balanced r-f circuits, to reduce re-radiation and spurious responses at harmonics of signal frequencies.

Jammer Alignment Systems

Various means have been proposed for automatically aligning a jammer with a victim

signal.[86] A theoretical study was made to compare some of these methods;[244] it was limited to electronic rather than mechanical tuning. A few of the mechanical methods are described above, in the discussions of the jamming systems into which they were incorporated.

Single Quado. The first approach to the problem was the development of a small visual indicator to be used with a radio receiver for the comparison of two carrier frequencies differing by less than 5 c, even though one or both of the carriers are keyed on and off at hand-telegraph speeds. The first unit developed, known as the Single Quado, contained a small motor-driven rotary neon Strobotron and a thyratron tube keyer stage.[96] With a steady received carrier the audio beat note of the receiver flashed the neon at the beat rate, and the flashes could be made to appear stationary by adjusting the frequency of the receiver beat oscillator. When the received carrier was keyed on and off, the flashes always appeared and disappeared in the same angular position on the Strobotron. The comparison with another carrier was made by switching the receiver to the new signal; and the speed of the neon motor provided the memory function.

Tests by the Navy indicated that the Single Quado instrument was not suitable for use in aircraft, primarily because of its susceptibility to noise and the frequency instability of the receiver beat-note output.

Dual Quado. Another development was the Dual Quado, similar to the Single Quado but with some circuit improvements.[115] Two rotary neons with a switching arrangement connected the beat note of two carrier frequencies to their respective Strobotrons. The Dual Quado was satisfactory for noiseless signals, but it was unsuitable for the application intended on account of the difficulty in adjusting the beat note under conditions of noise and random keying of one or both of the signals.

Stopwatch. A different approach to this problem was an automatic device known as Stopwatch for holding the jammer signal within a few cycles per second of the victim signal.[86, 112] Stopwatch was developed particularly for jamming telegraph signals operating in the frequency range from 1 to 20 mc. A demonstration model was designed for the frequency range from 2 to 5 mc which incorporated the essential components of a radio receiver, transmitter, and exciter, and a servomechanism. By means of a common heterodyne oscillator, it was possible automatically to maintain the frequency of the transmitter exciter to within 10 c of the received carrier frequency, when this carrier was keyed at hand-telegraph speeds. Complete jamming was obtained with a J/S voltage ratio of unity. Compared with existing jammers using random noise or some similar modulation, this jammer represents a saving in power of approximately 100 to 1.

On the basis of the experimental equipment, a preproduction model covering the desired frequency range was designed[338] and a small number manufactured, both commercially and by the Signal Corps. Since this set proved satisfactory, regular production was initiated.

Recommendations for Future Work. Probably the most effective AJ device known is c-w telegraphy. Good operators can copy intelligence through certain types of noise or jamming 20 db stronger than the signal; and to do an efficient job of jamming telegraphy, it is necessary to place the jammer within a few cycles per second of the victim signal. This is the unique purpose of Stopwatch, which distinguishes it from jammers using similar principles. It is believed worth while to develop the Stopwatch principle further and to develop equipment of various frequency ranges and powers for ground and airborne use as indicated by tactical problems.

8.4 GUIDED MISSILES JAMMERS AND ASSOCIATED EQUIPMENT

This section lists and describes the jammers and jamming systems developed in Division 15 for use against guided missiles. The distinction between communications and GM jammers is not always quite definite, since their frequency ranges are about the same, and many transmitters can be used for either purpose; indeed, some jammers, such as Dina, have been used against l-f radars also.

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8.4.1 Ground-Based and Airborne Jammers and Systems

Transmitters intended specifically to jam the control systems of enemy guided missiles could not be designed or built until information was available on the frequencies and control methods used. The first GM jammers, therefore, were communications jamming systems used for this purpose, or other transmitters hastily converted into jammers. The background of techniques and knowledge gained through the development of communications countermeasures, however, made it possible to design GM jamming transmitters in a surprisingly short time.

High-Power Ground-Based Jammer AN/GRQ-1

In July 1944, the Signal Corps requested four high-powered jamming transmitters for countermeasures use against radio-controlled GM. Specifications for the jammers were based upon intelligence reports, which were enlarged upon through reasonable engineering estimates and consideration of previous GM experience. These specifications required operation over a carrier-frequency range from 20 to 60 mc, with provision for rapid frequency adjustment over a 10-mc band while the equipment was in operation. The power output was to be at least 50 kw, and the output signal was to be 100 per cent amplitude-modulated by a square wave, with a 50 per cent duty cycle and a pulse-repetition rate between 100 and 15,000 c.

Modifications to Commercial Equipment. Since these jamming equipments were urgently needed, it was decided to modify existing 50-kw power amplifiers rather than to attempt a completely new design. A thorough survey of available equipments showed that three suitable commercial amplifiers with power supplies, built for use in f-m broadcasting transmitters, could be procured. These were ordered, and modification work was initiated immediately upon receipt of the first equipment. In addition, preliminary work was begun on the construction of a fourth equipment from available components.

The modified transmitting equipment, identified as the AN/GRQ-1, consisted of a variable-frequency, self-excited oscillator, utilizing a pair of Type 8009 vacuum tubes tuned by sections of transmission line; a keying modulator, providing the required square-wave modulation; a three-phase bridge-type rectifier, using six Type 869B mercury-vapor rectifier tubes; a power and interlock control panel; and a water-cooling system.[322] The input requirement of the equipment was approximately 125 kw of three-phase, 60-c power at 220 v, and the normal r-f output power was 50 kw with a plate efficiency of approximately 60 per cent.

The modification of the 50-kw amplifier involved its conversion into a push-pull (double Hartley) power oscillator using a plate transmission line as the frequency-determining element, with feedback capacitors from the plate of each tube to the grid of the opposite one. The adjustable plate line originally provided in the amplifier was extended, and additional shorting sliders and actuating mechanisms were provided to permit tuning over the required frequency range. The rectifier power supply which provided the high-voltage direct current for the power-amplifier stage of the original equipment was used without modification to supply plate power for the oscillator. A modulation system was designed and constructed to give the required waveform; it was composed of an electronic keyer, whose keying frequency was determined by a sinusoidal input signal from a conventional audio oscillator.

Concurrently with the modification of the power amplifier, h-f and l-f antennas for use with the jammer were designed. To provide for all required radiation patterns, the complete antenna system included four vertically polarized half-rhombic antennas and four horizontal rhombics. A system of transmission lines and switching circuits for both balanced and unbalanced operation linked the transmitter to the antenna system.

The modified transmitter was tested with a balanced dissipative transmission line load. After final tests were completed, the first unit was packed for shipment to the United Kingdom on August 27, 1944, and modification of the remaining two equipments was begun.

Installation. Before this shipment arrived,

SECRET

changes in the requirements of the Armed Services made unnecessary the use of the AN/GRQ-1 jamming equipment at a fixed site. It was decided that the engineers who had gone to England to aid in the installation of the jammer should undertake further modification, to render the transmitter mobile and to fit it for use as a general-purpose jammer in addition to its original function. The modification work was completed with actual radiation tests by December 8, 1944. In this mobile installation the entire AN/GRQ-1 equipment, including a single vertical half-rhombic antenna and a spare, was accommodated in five trucks for ready transport.

As a result of the above-mentioned changes in Service needs, the number of jamming equipments to be produced was decreased to three. Work on the fourth equipment was therefore stopped; but the modification of the two remaining equipments was completed, and the equipments were delivered to the Signal Corps.

The mobile installation involved many changes, generally of a minor nature, in the AN/GRQ-1 equipment. Mountings for many of the component parts of the equipment were strengthened or otherwise modified; and circuit changes to increase ease of operation and maintenance were effected. In addition to such modifications, designs were produced for a frequency-sweeping modulator arranged to swing the frequency of the main oscillator ±3 mc at a rate of approximately 100 c. Consideration was also given to the problem of using a search receiver in the immediate proximity of the AN/GRQ-1 equipment while the latter was in operation; and a "look-through" system was proposed as a possible solution.

Automatic Search Jammer (Broom)

Basically, the Broom-type automatic search jammer[320] originally intended for use against guided missiles such as the HS-293 comprised a radio receiver and a transmitter utilizing common LC circuits, whose resonant frequencies could be adjusted by a variable tuning capacitor. The common tuning capacitor was motor-driven, and as it rotated in one direction the capacitance of the tuned circuit was varied from a minimum to a maximum and thence to a minimum as the fixed and movable plates moved into and out of coincidence. Accordingly, the operating frequency of the receiver and the transmitter was swept back and forth through the chosen search band, 45 to 51 mc. The output of the receiver was amplified and applied to a trigger circuit which, when tripped by the reception of the signal in the search band, turned off the receiver and turned on the transmitter. At the same time, the drive motor was reversed. The timing circuit associated with the trigger circuit restricted the reverse operation of the motor and, after a chosen short interval, again reversed the motor and returned the transmitter and receiver to the initial search condition.

The time constant of the timing circuit was so chosen that in the presence of a continuing signal in the search band the tuning capacitor was turned back and forth, tuning the equipment through a narrow frequency band centered on the carrier frequency of the enemy transmission. The drive motor was reversed and caused to run backwards for a short period each time the receiver was tuned through the enemy signal. This operation continued as long as the enemy transmission was present. As soon as it was terminated, the motor was again allowed to run continuously in a single direction, re-establishing the condition for search operation.

Several experimental jammers were constructed utilizing these basic principles. In the most highly developed one, a superheterodyne receiver was used, and the transmitter and receiver utilized the same doublet antenna. The transmitting oscillator and the r-f stage of the receiver used a common LC tank circuit, the resonant frequency of which was adjusted by means of a pair of variable capacitors. These capacitors were ganged together with those in the local oscillator and mixer stages of the receiver and driven through reduction gearing by a two-phase motor, which was controlled by the receiver through a peak-firing trigger circuit. A vernier drive was used for the tuning capacitors, to reduce the width of the jamming band with respect to that of the search band. For this purpose, the single set of ganged tuning capacitors was driven through a standard

SECRET

bandspread tuning drive with a speed reduction of 5 to 1.

Tests on the completed equipment indicated that a jamming bandwidth of 100 kc could be obtained at the center of a search band extending from 45 to 52 mc with proportionately broader or narrower jamming bands at the limits of the search band. It was concluded that the Broom-type jamming system could be used successfully and with good efficiency for the jamming of a single enemy transmission occurring within a chosen search band; if two or more enemy signals, however, should occur simultaneously in the search band, only one of them could be jammed with a single Broom. Furthermore, additional Brooms could not be operated in the same search band for jamming a second or third enemy signal, because one Broom would then jam another unless all were carefully interlocked. In view of these conclusions, further development work on the Broom-type jammer was abandoned in favor of other approaches to the general problem.

Automatic Search Jammer (Beagle)

An experimental model of this type of automatic search jammer[329] (also intended for use against guided missiles) was developed. It was a single-frequency jamming transmitter which automatically tuned itself to the frequency of the victim signal, in the range 46 to 51 mc. It consisted basically of a receiver, a control unit, a modulated transmitter, and two servo systems.

The receiver servomotor drove the ganged tuning capacitors in the receiver (and also a rough tuning capacitor in the transmitter) to sweep the desired band. When a signal was encountered, the receiver output actuated the control unit, which caused the receiver servomotor to tune the receiver to the frequency of the incoming signal; a mechanical brake was then applied to the receiver servomotor shaft. An instant later, the jamming transmitter was turned on automatically, and the control unit caused the transmitter servomotor (which drove a vernier tuning capacitor) to tune the transmitter to the same frequency as the receiver, thereby jamming the incoming signal. After a preset transmission time of 10 sec, the transmitter was turned off and the cycle of operation was repeated.

In the final experimental model, the equipment was contained in two cases whose gross weight was approximately 45 lb. The receiver was adjusted to operate on signals from 100 to 20,000 μv in the band from 46 to 51 mc. With these incoming signals, the frequency of the jamming signal always matched that of the incoming signal to within 3 kc. The maximum length of time necessary to locate the enemy signal and then tune the transmitter to that frequency was 13 sec. The transmitter power output was about 38 w unmodulated and about 50 w modulated with 1,000 c. No production models of this automatic search jammer were built.

Signal-Repeating Jammer (Piano)

To cope with the possibility that the type of modulation necessary to control well-designed guided missiles might be so complex as to prevent effective duplication for jamming purposes, another type of jammer was studied. Although this equipment was never developed to a working model, enough work was done to indicate the general feasibility of the approach.[332] The functional procedure proposed for the Piano is as follows. (1) Listen over the entire monitored band for an interval of time, memorizing the carrier frequency of all signals received. (2) Memorize simultaneously the frequency composition of the modulation on all signals. (3) Transmit on each of the memorized frequencies a carrier modulated with the proper memorized modulation. (4) Alternate the receiving and transmitting intervals in such a fashion as to maximize the jamming and minimize the tendency for the Piano to become a repeater.

The "memory" for carrier frequencies consisted of a bank of primary oscillators evenly spread across the monitored band. These oscillators were normally quiescent, but a particular oscillator would go into sustained oscillation when a signal appeared in its frequency band. A bank of such special oscillators was designed and built to work from the output of a broadband amplifier. A more accurate memory could be attained by using a second bank of oscil-

lators with frequencies spaced up to half the difference between the frequencies of the primary band, and by operating this second bank with the beat note between the received signal and the "triggered" oscillator. With five banks of oscillators covering a 10-mc band at 50 mc, it is ideally possible to reproduce a given frequency to within 10 c. Such a memory system would determine the frequency of all sidebands as well as that of the carrier, and consequently memorize the modulation as well as the carrier. This plan provided the basis for the first concept of the Piano.

Since the beat note between the incoming signal and the first memory oscillator was the arithmetic difference between the two frequencies, it was necessary in reconstituting the signal for transmission to use the sum and difference of the primary oscillator frequency and the interpolation oscillation frequency. In practice, it was necessary to transmit the primary oscillator frequency also, for this component could not be readily suppressed.

Each added bank of interpolation oscillators therefore tripled the number of frequencies radiated. In the case of a five-bank Piano, the transmission of one signal would require the transmission of 80 other near-by frequencies, with the overall efficiency consequently low. The energy in the additional signals would not necessarily be completely wasted, however, since they would all be in the immediate vicinity of the desired one.

A second version of the Piano called for only one bank of primary oscillators and one of interpolation oscillators. This system, of course, required the transmission of only two other near-by frequencies, with a consequent improvement in overall efficiency. In this version of the Piano the modulation was to be memorized by a group of oscillators in the l-f range which were subjected to the modulation envelope of the carrier. Ideally, a reasonable number of logarithmically spaced oscillators should be able to memorize the required modulation frequencies. Once the transmission frequencies were memorized, it would be a relatively simple matter suitably to mix, amplify, and transmit the output of the memory oscillator.

Low-Power Airborne Jamming System AN/ARQ-8

The AN/ARQ-8 jamming system consists of a transmitter (Dina) of the suppressed-carrier type and an associated receiver (Dinamate). The principles of this type of transmitter have been discussed to some extent previously (Section 8.2). Other carrierless Dina-type jammers were developed for special purposes in the communications frequency range,[167, 178] but the ARQ-8 was the only one produced in any quantity. (The higher-frequency Dina, AN/APT-1, was used extensively as a radar jammer—see Chapter 11.)

The ARQ-8 was developed originally for use against communications and covers frequencies from 25 to 100 mc. Because it was more widely used as a radar jammer, however, Chapter 11 contains a more detailed discussion of the equipment.[367, 557] Its greatest application outside the radar field came as a GM jammer,[421] since it was available and since it covered the right frequency range with a reasonable amount of power.

High-Power Airborne Jamming System AN/ARQ-11

During the summer of 1944, at the request of the Army Air Forces, development work was begun on a wide-range, 1.5-kw, airborne jammer for use in the GM countermeasures program. This work resulted in the construction of ten preproduction models. It was originally planned to build 100 jammers, designated AN/ARQ-11, but in the course of military events, this number was deemed unnecessary and the construction program was curtailed. A ship-borne model was built, known as the AN/SRQ-11.

The airborne jamming system AN/ARQ-11 operated at frequencies between 20 and 70 mc. It consisted essentially of a receiver and a self-excited transmitting oscillator.[327] Three modes of operation were provided: (1) *Stand By*—the radio receiver operating and all filaments lighted; (2) *Search*—the power oscillator generating the unmodulated carrier at approximately half of the full power; and (3) *Operate*—the power oscillator operating at

SECRET

full power and generating a carrier which is square wave-modulated at a frequency between 100 and 15,000 c. The average power output depended on the carrier frequency—approximately 1,700 w at 20 mc and 400 w at 70 mc.

In operation, the frequency of the power oscillator was tuned to that of the enemy transmitter by listening through headphones to the difference frequency between the unmodulated carrier (at low power) and the enemy transmitter as the oscillator frequency was varied. The receiver selected and amplified this difference frequency. When the power-oscillator frequency was the same as that of the enemy transmitter, the full power was turned on and the output keyed at a predetermined audio frequency.

In February of 1945, one AN/ARQ-11 was installed in a B-24 airplane. The rear bomb bay of the bomber was partitioned into two compartments, with the power plants for the ARQ-11 located in the front section and the set itself in the rear section. The equipment was satisfactorily flight-tested.

Details of Equipment. In the production model, the AN/ARQ-11 equipment consisted of eight major units: the radio receiver (R-21/ARQ-11), which included five tuning units and weighed 24 lb with one unit in place (the others weighed 4 lb each); the audio oscillator (O-28/ARQ-11), weighing 18 lb; the modulator unit (MD-42/ARQ-11), weighing 41 lb; the power oscillator (T-102/ARQ-11), which included seven sets of grid and plate plug-in coils and five antenna coupling coils and weighed 72 lb with one set of coils (the remaining coils weighed 13 lb); the three rectifier units (PP-130/ARQ-11), weighing 59 lb each; and the control unit (C-187/ARQ-11), weighing 75 lb. The necessary cables and mounting trays were also included. The total weight of the ARQ-11 was 436 lb, exclusive of cables and mounting trays but including all tuning units and plug-in coils. The maximum power requirement was 46 amp at 115 v, 400 c, and 23 amp of 28-v direct current.

The radio receiver[323] was used with any one of the five plug-in tuning units which fitted into the front of the receiver chassis, each covering one of the five 10-mc bands between 20 and 70 mc. These units differed only in the values of some circuit elements. The input signal from the antenna was applied to a broad-band r-f amplifier followed by a mixer stage where it was beat against a heterodyning signal either from the power oscillator or from a local oscillator included in the tuning unit. The audio output then went through a two-stage amplifier in the receiver chassis, which also contained a power supply.

The audio oscillator[317] contained a two-stage oscillator section, a two-stage output amplifier, and a power supply. It supplied an audio input signal for the modulator unit, with a frequency between 30 and 30,000 c. The modulator unit was arranged to control the operation of the power oscillator by providing the proper grid excitation for the three modes of operation, and included a clipper stage, a 3-mc local oscillator, a full-wave rectifier, an output keying stage, and a power supply. Control relays, operated from a selector in the power oscillator, effected the appropriate circuit changes to permit the selective operation of the set. The keyer system was of somewhat unconventional design. The sinusoidal audio input was amplified and shaped to a square wave which was used to key a low-powered local oscillator; the output was rectified and applied to the grids of the main modulator tubes.

The power oscillator comprised a push-pull oscillator of the tuned grid-tuned plate type, and was provided with a series of plug-in coils permitting operation from 20 to 70 mc. Each of the three identical rectifier units[324] contained a rectifier filament transformer, a plate transformer, two rectifier tubes, and a filter choke. The outputs of the three rectifier units were brought into the control unit and combined in parallel to form the plate supply for the power oscillator.

The control unit[324] served as a power distribution point for all the ARQ-11 units and as a junction point for some of the interunit connections. Located in this unit were the relay system which makes the power connections, an overload circuit breaker and a filter section for the power-oscillator plate supply, pilot lights, controls, and all fuses employed in the ARQ-11.

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8.4.2 Ship-Borne Jamming Systems and Amplifiers

One jamming system requiring only very brief mention is the AN/SRQ-11 (XN-1). This is the ship-borne version of the AN/ARQ-11 (Section 8.4.1, just preceding), of which one model was built.[327] This equipment consisted of four major units: the radio receiver, the modulator unit, the radio transmitter, and the power unit. The first three units mentioned were virtually identical with the corresponding ARQ-11 units. The power unit replaced the control unit and the three rectifier units of ARQ-11. This system operated on a single 115-v, 60-c line.

Medium-Power Jamming System, Type MAS

On April 18, 1944, the Naval Research Laboratory requested the engineering, development, and production of equipment for use as a countermeasure against the German HS-293

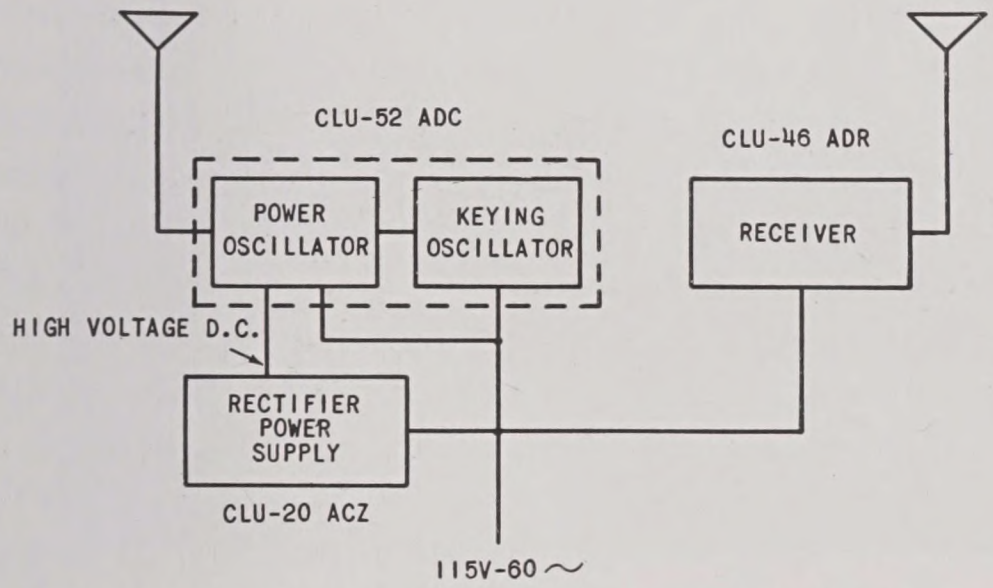


Figure 1. Block diagram of Type MAS shipboard jamming equipment for use against guided missiles.

radio-controlled glide bomb[312] and the PC-1400-FX radio-controlled bomb.

The necessary jamming system was produced and called shipboard jamming equipment, Type MAS, and the first complete unit was shipped on May 3, 1944. Thereafter, 49 additional equipments were constructed, and 47 of them were shipped between May and October for installation in destroyers, destroyer escorts, escort carriers, and transports. A representative was sent to England to supervise installations of the equipment in several troop transport vessels.

The MAS equipment shown in block form in Figure 1 was arranged to detect the carrier frequency of an enemy control signal and to transmit a jamming signal on the same frequency.[313] The jamming carrier was square wave-modulated at 1,000, 1,500, 8,000 or 12,000 c, and the modulation was interrupted for 10 msec of every 100 msec. As shown in the block diagram, the equipment comprised four major units.

Details of Equipment. The radio receiver (CLU-46ADR) could detect enemy signals in the band from 41 to 51 mc. The radio transmitter (CLU-52ADC), which was tuned to the enemy carrier as indicated by the receiver, radiated a relatively strong a-m signal with the modulation characteristics outlined above. A rectifier power unit (CLU-20ACZ) supplied high-voltage direct current for the operation of the transmitter, and a dummy load was provided for testing the transmitter without broadcasting any appreciable energy.[315]

The broad-band heterodyne receiver was designed to operate from a 70-ohm antenna (within a 5:1 standing-wave ratio). Although a local oscillator was included, the receiver was intended to operate primarily with a portion of the transmitter output as the heterodyning signal. For this purpose a part of the radiated signal from the transmitter was picked up by the receiver antenna and passed, together with the enemy signal, through a broad-band r-f amplifier stage to a mixer. The amplified a-f beat note was applied to headphones, and in operation the enemy carrier signal was heterodyned to zero beat for precise tuning.

The transmitter was tunable over the same range as the receiver and included a power oscillator, a keying oscillator, and a mechanical switch to interrupt the action of the keying oscillator for 10 out of each 100 msec. The power oscillator could supply either 150 w unmodulated r-f power or 250 (average) modulated power to a 50-ohm antenna system (within a 2:1 standing-wave ratio). The keying oscillator permitted the power oscillator to be modulated by square waves at any one of the

SECRET

four frequencies mentioned above. The entire equipment worked from a 115-v, 60-c source, and the control circuits allowed three types of operation: Stand By, Search, and Operate.

Operation. In the operation of the MAS equipment, the frequency band of the expected enemy signals could be monitored in either of two ways. The controls might be set to Stand By, so that only the receiver was operative and the local oscillator was used for tuning. Alternatively, the Search setting could be used, in which case the power oscillator was operative (at low power) as well as the receiver, to produce an unmodulated r-f signal used instead of the local oscillator output. In either event, after an enemy signal was detected and the carrier frequency matched, the equipment was switched to the Operate condition, with the transmitter giving full, modulated r-f power.

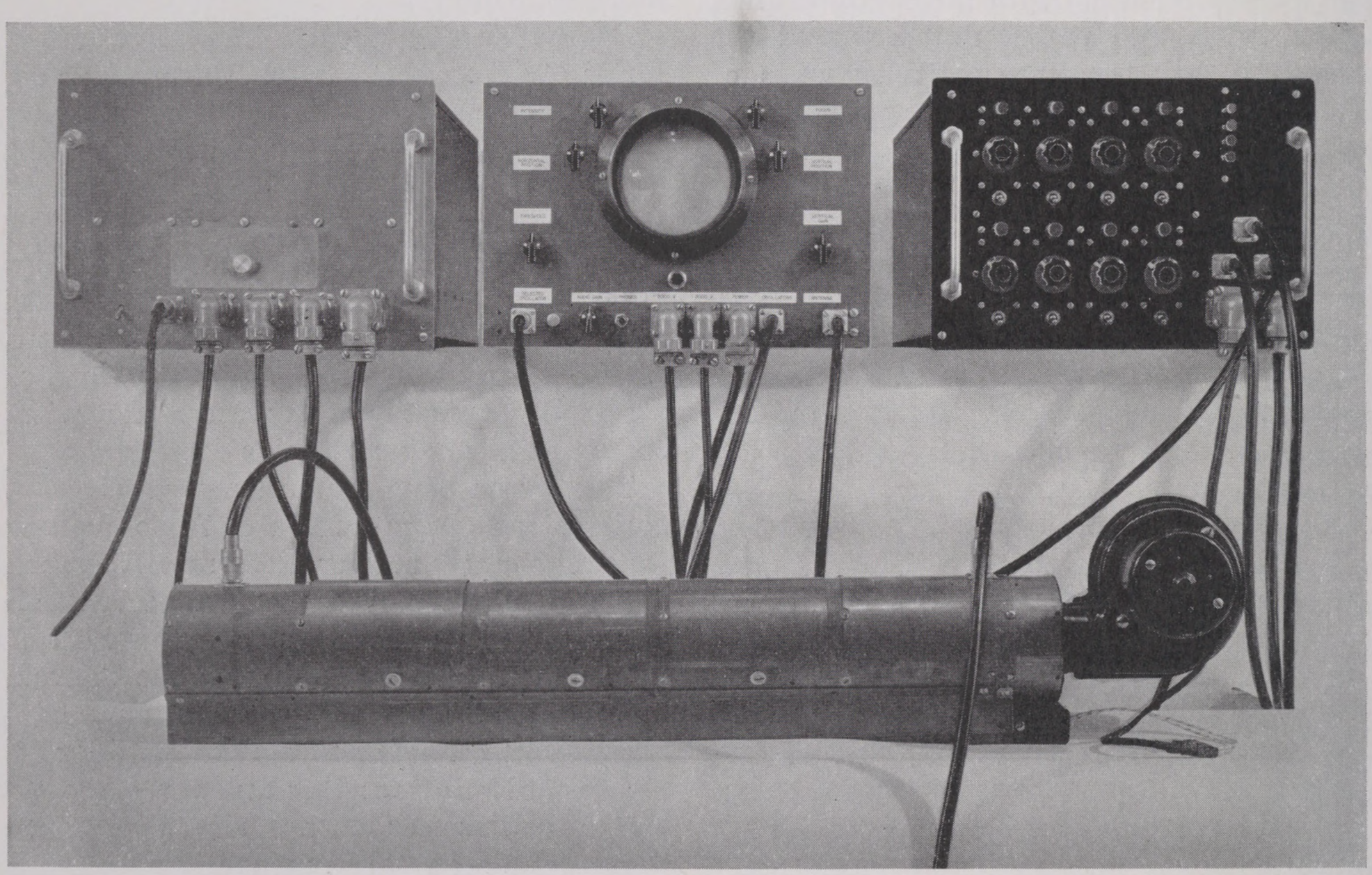


FIGURE 2. Photograph of prototype of multiple-channel jamming system, AN/SRQ-1.

MULTIPLE-CHANNEL JAMMING SYSTEM AN/SRQ-1

The AN/SRQ-1 jamming equipment[326] was developed as a countermeasure against radio-controlled GM and could jam simultaneously as many as eight enemy signals in the band from 46 to 51 mc.

Signals occurring in this search band were monitored with a superheterodyne receiver and presented on the screen of a cathode-ray oscilloscope as individual positive pips. The receiver was tuned across the search band in synchronism with the horizontal sweep of the oscilloscope, so that the position of a pip on the oscilloscope screen indicated the frequency of the detected signal. Eight local oscillators provided for generating an equal number of independent r-f signals, whose frequencies could be set anywhere in the search band. The local oscillators could be turned on separately, and their signals appeared on the oscilloscope screen as negative pips.

A prototype was constructed, and a photograph of its four units is shown in Figure 2. The receiver, timer, and cathode-ray oscilloscope are in the center unit, and the bank of local r-f oscillators, the keyer, and the automatic power-control system in the right-hand

unit. The cylindrical unit in the foreground is the r-f power amplifier and the left-hand unit contains the several power supplies required for the operation of the equipment.

Operating Details. In the operation of the equipment, one local oscillator was turned on for each enemy signal detected and its frequency adjusted until the negative pip coincided visually with a positive pip. More precise frequency matching was accomplished by means of an aural-monitoring channel, in which each of the local-oscillator signals in turn beat against the received signal; the local oscillator frequency was then adjusted to obtain an a-f beat note with the enemy signal to which it was most closely tuned. The locally generated r-f signals, each tuned accurately to an enemy transmission, were then amplified and radiated.

If the local r-f signals, however, had been transmitted continuously, the jamming signal would have made further search and monitoring impossible. Accordingly, search and jamming periods were alternated at a cyclical rate of 10 c, the jamming period occupying 90 per cent of each 100-msec cycle. This repetition rate was high enough that the visual presentation of the signals on the oscilloscope appeared continuous. The search-jam cycle was produced by a timer which first permitted operation of the oscilloscope and the aural-monitoring channel for 9 msec, then turned on the jamming equipment for 90 msec, and finally provided a 1-msec delay period in which the receiver circuits could recover from the overload imposed by the jamming signal.

In the operation of the transmitter the signals from the local oscillator were combined, keyed at one of four audio frequencies, and applied to a linear r-f power amplifier. The keying circuit square wave-modulated the combined r-f signals optionally at 800, 1,000, 10,000, or 12,000 c. The power amplifier was linear, to avoid mixing and the consequent radiation of power at the unwanted sum-and-difference frequencies. It provided uniform response over the band from 46 to 51 mc with an average output of 10 w. Since the input signal components might add in amplitude and overload the amplifier, an automatic power-control system was provided to maintain the input at a low enough level to preserve the linearity of the amplifier. In this control system, part of the amplifier output operates a servomotor, which in turn adjusts an attenuator in the input circuit.

1-KW AIRBORNE OR SHIP-BORNE AMPLIFIER

At the request of the Army Air Forces, work was started on the development of a 1-kw amplifier for airborne or shipboard use against GM. This amplifier was to be capable of covering any 5-mc band in the 40- to 60-mc range and was to be driven by the modulator unit being designed for the AN/SRQ-1.

The project was terminated before completion; however, several experimental amplifiers were built to test various types of power tubes and associated broad-band circuits. The preliminary performance figures for several tube types in push-pull at 50 mc are given below:

833-A Bandwidth 7 per cent, peak efficiency 48 per cent.

304-TL Output 700 w at 60 per cent plate efficiency; 10 per cent variation in output power at 10 per cent bandwidth.

8014-A Output 1,100 at 50 per cent plate efficiency; 20 per cent variation in output power at 12 per cent bandwidth.

827-R Output 2,000 w at 65 per cent plate efficiency; bandwidth about the same as for 8014-A.

8002-R Output 2,700 w, amplifier efficiency 55 per cent; 15 per cent variation in output power at 10 per cent bandwidth. The power output of this amplifier was limited by the power supply.

SECRET

Chapter 9

NONRADAR ANTIJAMMING TECHNIQUES

9.1 INTRODUCTION

THE DEVELOPMENT and use of antijamming [AJ] techniques and equipment is related to radio countermeasures [RCM], since AJ is in effect a counter-countermeasure. Studies of the vulnerability of Allied equipment to both friendly and enemy jamming techniques resulted in the development of certain AJ practices. It is important to recognize the fact that it is generally impossible to protect a specific communications channel or set against a concerted and properly directed jamming attack. The AJ precautions should therefore be considered from the viewpoint of the whole communication network for a given area.

Probably the most important basic consideration in AJ techniques is adequate operator training and experience. There is no substitute for the ability and will to overcome jamming. For several of the more generally effective forms of interference, such training is the most effective AJ measure yet developed.

This chapter summarizes the various projects established at laboratories under the auspices of Division 15 which were concerned with AJ techniques for equipment other than radar and with tests made to measure the vulnerability of such equipment to jamming. Most of the work was carried out by the Federal Telecommunications Laboratories, Inc., under contracts OEMsr-936 and OEMsr-937, the Airborne Instruments Laboratory under contract OEMsr-1305, Jansky and Bailey under contract OEMsr-1024, and the Radio Corporation of America under contract OEMsr-895.

Many of the fundamental AJ considerations are the same whether the equipment to be protected is a radar or some other electronic device; this is especially true of the conclusions as to the importance of operator training. The radar AJ techniques developed are described in Chapter 13, while Chapter 10 includes some considerations on the protection of proximity fuzes. The jamming techniques against which the equipments are to be protected are described in Chapter 8 and also in Chapter 10.

9.2 GENERAL ANTIJAMMING STUDIES

In the course of the AJ program, a certain amount of attention was given to basic AJ principles, which do not involve the use of any particular apparatus but are concerned with the proper design and employment of equipment. In addition, general studies were made to determine the effects of various jamming signals on the different types of receivers and circuits. Descriptions of the jamming signals used can be found in Sections 8.2.2 and 13.3, together with some conclusions on their effectiveness in general. Special studies were carried out on the AJ properties of detectors and mixers. The results of this work were of considerable help in evaluating the effectiveness of proposed jamming methods (see Section 8.2).

The results of these general studies were collected, together with the results of the vulnerability measurements described in Section 9.3, and compiled to form a Handbook of Communications AJ.[288, 344] This handbook was intended largely for the use of receiver designers, in order that they might avoid design practices which have proved to be bad from an AJ standpoint. The compilation was begun by the Communications Section of the Division 15 AJ Practices Panel (see Section 13.2.1), and was completed by Jansky and Bailey.

9.2.1 Basic AJ Principles

There are two fundamentals to be remembered if equipment is to be properly protected from enemy jamming. The first is that the equipment should be well-designed from an AJ point of view—that is, the vulnerable types of

SECRET

circuits should be avoided. The results of the investigations into the relative susceptibility of different circuits are summarized in the later paragraphs of this section.

The second fundamental is that the equipment should be used in such a way as to render jamming as difficult as possible and to nullify the effects should it occur. For example, in selecting the site for a station, consideration should be given to the possibility of enemy jamming, in addition to the usual precautions. Communications systems in the higher-frequency bands should be located so that they are screened against jamming from enemy-controlled territory. This is not always possible, of course, but the technique should be kept in mind.

Frequency Coverage

The coverage of a communications network should be planned with the idea of providing the required service in the area involved in spite of the anticipated amount of enemy jamming. In other words, consideration of the AJ problem should not be limited to the study of single pieces of equipment at particular sites, since, if a set is within range of the enemy, it can almost certainly be put out of action if the enemy concentrates his efforts on it.

The important consideration in planning service for a given area is to provide both flexibility and diversity of frequency. The latter may be achieved by using equipment, for each type of service, which operates in widely separated frequency ranges, so that if one channel is jammed another may be used. Frequency flexibility involves the means for selecting a number of different operating frequencies in a given range.

Although frequency diversification cannot always be achieved, it is highly desirable, and this fact should be kept in mind in any plan affecting large areas. When equipments operating in a new portion of the spectrum are added to networks already in use, the older sets should not be removed from service, both in order to have various channels available and to keep from revealing the presence of new apparatus on other frequencies.

Moreover, it is important to use the whole band of frequencies over which a given type of equipment can operate. This practice forces the enemy to spread his jamming effort over a wider band and thus reduce the strength of the interference in any given channel. The ability to make small (or large) changes rapidly in the operating frequency of a set is also important, since this makes it possible to tune the set away from the jamming to a region where the interference is less effective or absent.

Operator Training

The importance of training operators properly can hardly be overemphasized (see Sections 9.3 and 13.5). The training should include not only instruction in the use of the various AJ devices and attachments which may be available, but continual experience in reading through jamming and in the proper use of the controls available on the equipment. It has been proved by actual operations in World War II that the efficiency of operators is greatly reduced the first time they are exposed to jamming, but that it improves steadily with successive exposures. This experience can be obtained, obviously, at less cost during training than in battle.

In all communications sets, the operator has a variety of controls at his disposal, and it is essential that he be familiar with their use in order to minimize the effects of interference. Often what might be considered abnormal adjustments (especially of the receiver gain control) result in improved AJ properties. For example, limiting action in communications receivers greatly decreases the effectiveness of spark and f-m jamming; but many receivers do not have limiting circuits. By turning up the volume controls, however, limiting action can be obtained by overloading the receiver, the headphones, or even the ear.

The training of operators is materially aided by the use of suitable phonograph records, and jamming signal generators are also important training adjuncts. The use of these aids should not be limited to schools, for it is only by constant exposure to jamming that an operator gains and maintains his ability to work through interference. Such devices, therefore, should be made available to operators and used periodically for training.

9.2.2 Comparison of Communications Systems

A number of tests were made comparing the relative communication efficiencies of an a-m system, a wide-band f-m system, a narrow-band f-m system, and a telegraph system; the comparison was made on the basis of readability through interference consisting of random noise, impulse noise, and continuous wave.[82] These studies indicated several modifications which could be used to improve reception in the presence of jamming. One was the insertion of an audio limiter in the modulation input of the transmitter, to increase the average modulation level.[84] This change produced about 6 db improvement for amplitude modulation in the presence of random and impulse noise. For other systems and types of interference, the improvement effected was small. Another arrangement which was useful under certain conditions of interference was a narrow-band f-m adapter.[97] Such an adapter, with an i-f bandwidth of approximately 8 kc, was designed specifically to be used with the Signal Corps radio receiver BC-603D. While the use of this AJ device resulted in a small sacrifice in speech reproduction quality, there was little impairment in the intelligibility. Prototypes of the narrow f-m adapter were delivered to the Signal Corps.

9.2.3 Jamming of Telegraphy

An investigation was made to determine the best conditions for jamming telegraphy and the best possible protection against such jamming.[159, 160] Previous tests had indicated that the jamming of telegraphy was a difficult problem. A very extensive study was conducted with a large number of different types of jamming signals at audio frequencies, at radio frequencies, with and without limiters, and with actual Army and Navy communications sets,[162] as well as with laboratory equipments. The tests covered both barrage and spot-frequency jamming. The types of interference used included resistance noise, multiple tones, variable-pitch sawtooth jamming, random pulses similar in character to telegraphic code, and so forth.

The research was also concerned with the human factors, such as experience of the operator, fatigue, nervous reactions to different types of noise, etc.

Results Obtained

All the experiments indicated that results can be reproduced accurately when confined to laboratory tests and that jamming efficiency can be defined when the human factor is eliminated. In these conditions, the determining factor is not the type of jamming signal used but the accurate tuning of the carrier frequency. Only signals within 20 c of the carrier frequency have any appreciable effect. Resistance noise is probably the most effective modulating signal,[161] but other types of modulation are almost as efficient when the carrier is properly tuned.

The introduction of limiters in a receiver does not protect against jamming if the jammer is modulated with "undistorted" resistance noise. By "distorted" resistance noise is meant noise signals which have been submitted to nonlinear effects such as clipping or saturation. Distortions like these, which change the frequency spectrum of the noise, might reduce the efficiency of the jammer in significant proportions when the receiver is protected by limiters. When no limiters are introduced, even distorted noise is effective.

Most of the results obtained in the laboratory are reproducible in actual practice with one considerable difference—the experience of the operator. An experienced operator represents a protection against jamming which can be estimated at roughly 12 db, plus an additional factor of 6 to 8 db which represents the difference in susceptibility to fatigue. This fatigue factor is due to the fact that even an experienced operator loses some of his ability to distinguish signals through noise after 20 or 30 min of jamming but that for an inexperienced operator such an effect does not exist.

All these factors are true only when jamming is not complete. Technically, it is possible to obtain complete jamming of telegraphy with a very good efficiency (i.e., with equal field strength for the jammer and the desired signal) if absolutely accurate frequency tuning can be achieved.[163]

SECRET

9.2.4 Jamming of Pulse Communications

A general study was carried out to investigate the jamming and antijamming possibilities of pulse communications systems.[114] The investigations, in general, were concerned with voice-modulated communications systems using modulation of the pulse frequency or phase. The pulses were usually about 0.8 to 1 μsec in length, and the repetition rate was in most cases either 10 kc or 18 kc in the unmodulated condition.

Scope of Experiments

In the systems employing modulation of the pulse frequency, the peak deviation due to the frequency modulation was about 4.5 kc when the 10-kc rate was used; for the 18-kc rate, the peak deviation was about 12 kc. In the pulse phase-modulation system, pulses approximately 0.8 μsec long were employed at a 10-kc repetition rate and were modulated approximately one-quarter of a radian by voice.[92]

The various types of jamming signals tried[104] included: (1) continuous wave unmodulated or continuous wave amplitude-modulated 100 per cent with a-f random noise; (2) short pulses, unmodulated or frequency-modulated with a-f random noise, at various pulse rates; (3) pulses, phase-modulated with a-f random noise using mark factors of 2, 30, and 50 per cent; (4) a radio spectrum of random noise both gated and not gated.

Results and Conclusions

Several types of receivers were used, including a trigger-type circuit as well as a normal limiter and discriminator system. Although the trigger-type circuit made a highly desirable receiver from the standpoint of simplicity and ability to receive wide deviations, it was easily jammed, since interfering pulses would trip the trigger circuit.

An important improvement in the AJ features of pulse receivers was a pass circuit or pulse-amplitude selective circuit. This pass circuit was combined with an automatic gain control circuit, so that the receiver was selective to only a narrow range of pulse amplitudes and pulses of higher or lower amplitude were not transmitted. The method was a very effective AJ device.[103]

In order to obtain the full advantage of the noise reduction possible with a pulse f-m system, the i-f amplifier was followed in some cases by clipper stages. These were circuits which took a horizontal slice out of the center portion of the pulse, thus removing amplitude variations and noise between pulses as long as the amplitude of the pulse was above the threshold level. The threshold level was taken as the point where the peak amplitude of the pulses was twice that of the noise. The pulses from the clippers were differentiated to remove the width variations caused by random noise[108] and were then used to trigger a pulse-lengthening circuit.

The best method for jamming a pulse communication system is, of course, the one which uses the least power to accomplish the jamming. The power required for complete jamming is quite variable, depending upon circuit arrangements, and there is no best method unless the circuit details of the victim receiver are known. On the average, when this knowledge is unavailable, the best jammer was found to be the r-f noise spectrum with 50 per cent gating. The most effective method found for reducing the susceptibility of a receiver to jamming was the pass circuit. The receiver for f-m pulses should employ differentiation and either a balanced-type discriminator or an unbalanced-type discriminator with a good limiter, whichever is most convenient for a particular case. It was found helpful to have a gain control on the i-f amplifier and adjustments on the clipper stages.

In addition to the pulse jamming and AJ studies, a preliminary report was prepared covering the detection and identification of various possible systems of pulse communication, and the measurement of variables such as the average pulse rate, the pulse length, and the type of modulation.[100]

9.3 VULNERABILITY OF COMMUNICATIONS RECEIVERS

A great many measurements were made of the vulnerability to jamming of the radio communications circuits and receivers used by the

SECRET

Armed Services. Similar measurements made on enemy communications sets are discussed in Chapter 8 (Section 8.2.3), and those on United States radars in Chapter 13 (Section 13.4.1). Any AJ measures encountered or developed in the course of this work or suggested by the results were of course reported. No special equipment was developed in such investigations except what was necessary to conduct special jamming tests.

In order to carry out the test program, a separate laboratory was set up in Washington, D. C., by making alterations to an existing building. Special rooms which were individually shielded and soundproofed were constructed; general laboratory and office space was provided as well, to permit all the work to be concentrated at one location. The facilities were sufficient to provide for measurements on several types of equipment by different groups or for the simultaneous testing of as many as four different receivers with a single transmitter-jammer setup.

9.3.1 Test Methods and Techniques

When the work was started, there was no information available as to the type of jamming signals which might be encountered; it seemed reasonable, therefore, to use those signals which were easily obtainable in the field as well as those which were to be used against the enemy. As a result of this policy, all vulnerability tests were made using the following signals as interference: (1) continuous wave, (2) continuous wave amplitude-modulated by sine wave, step tones (Bagpipes), and noise, (3) f-m continuous wave using sine-wave, step-tone, and noise modulations, all with different frequency deviations to give a variety of bandwidths, (4) wide-sweep f-m signals giving barrage jamming to cover bands from 1 to 4 mc wide, and (5) pulses, with various widths and repetition rates.

In order to obtain the various jamming signals, special signal generator equipment was required, and most of this was provided by the General Radio Company under contract OEMsr-1005 (see Section 5.2.1). In addition, it was necessary to build a pulser which gave calibrated pulse voltages over a frequency range from 2 to 150 mc with output levels up to 20 or 25 v into a 75-ohm load. Details of the methods for making the vulnerability tests are described in the various references given below. In general, the method was as follows: the jammer and the desired signal were introduced in the input of the receiver through mixing boxes, and the relative levels carefully set for the desired conditions. In cases where a receiver operated normally with a certain type of transmitter, the desired signal was obtained from this transmitter with the output suitably attenuated for the test.

Considerable study was made to determine the most suitable type of intelligibility tests to be used, with the result that the following criteria were established: (1) For code tests employing modulated or unmodulated continuous wave, transmission of five-letter unpronounceable groups was made at a rate of ten words per minute, and the jamming effectiveness was rated as the percentage of code groups missed out of a total of 20 groups for each test; a group was considered incorrect if two characters or more were missed. (2) For voice communication, each test consisted of ten sentences of a certain type.[833] The jamming effectiveness in this case was taken as the percentage of test sentences incorrectly received, where the determination of correct or incorrect reception was based on whether or not the listeners understood the thought contained in the sentence and could repeat the key words. In general one talker and two listeners were used for each test. Definitions and test methods for jamming effectiveness testing were agreed upon jointly by members of the research groups most closely connected with the problem.[262]

9.3.2 Results of Tests

It was found that, in general, the communications equipment in use by the Armed Services can be divided for the purpose of vulnerability studies into the following six broad groups.

1. High-frequency a-m equipment: general-purpose fixed and mobile sets employing amplitude modulation for both voice and code communication, in the frequency range 1.5 to 18 mc.

2. Very-high-frequency a-m equipment: v-h-f aircraft and ground-to-air sets employing amplitude modulation for voice communication, in the range 100 to 150 mc.

3. High-frequency f-m equipment: mobile and hand-transportable sets employing frequency modulation for voice communication, in the frequency range 20 to 50 mc.

4. Very-high-frequency f-m equipment: point-to-point and relay equipment using frequency modulation for voice, facsimile, and teletype printer, in the range 50 to 100 mc.

5. Pulse systems: sets using a series of pulses whose phase or repetition rate is modulated for voice communication.

6. Special equipment: communications systems specifically designed to have good AJ characteristics, and special-purpose equipment, such as mine detonators.

Group (1): High-Frequency Amplitude-Modulated Receivers

The jamming susceptibility of the following receivers in group (1) was investigated: the BA-348-R,[268] the BC-342-N,[270] the BC-312-N,[270] the BC-652-A,[272] the BC-669-C,[273] the BC-654-A,[274] and the ARB.[279, 281] A comparison was made of the vulnerability of all but the last of these receivers.[275]

In general, the results can be described as follows. An unmodulated carrier was not an effective jammer even when detuned to give an audible beat. Ordinary amplitude modulation with a fixed tone (sine wave), particularly when detuned by an audible beat, caused jamming to occur at jam-to-signal [J/S] ratios of 6 to 14 db. Jammers amplitude-modulated with noise were approximately 10 db less effective than a pure tone, whereas step tones were most effective when detuned approximately 1 kc, consistently giving J/S ratios of 4 to 8 db. Jammers frequency-modulated with noise or step tones, and having bandwidths of the same order of magnitude as the receiver, were most effective, causing jamming at J/S ratios of approximately 0 db (i.e., jamming strength equal to signal strength). Pulses were relatively ineffective against receivers of this type; although they often caused discomfort to the listeners, it could be alleviated by proper installation of a good peak limiter. As expected, c-w and modulated c-w communication was superior to voice against all of the jammers employed.

Group (2): Very-High-Frequency Amplitude-Modulated Receivers

The vulnerability of four different receivers in group (2) was studied; namely, the AN/ARC-4,[264] the BC-639-A,[265] the BC-624-AM,[266] and the AN/ARC-1.[277] A comparison[267] of the first three of these was carried out. In addition, a series of tests was made on the BC-624-A to determine the vulnerability to pulses, as affected by the use of various types of limiters.[260]

Receivers in this frequency range were characterized, in general, by greater bandwidths than those in the lower-frequency ranges, and they were therefore somewhat more vulnerable to jammers whose energy was distributed over a considerable portion of the spectrum. To offset this drawback, the greater bandwidths made peak clippers more effective against impulse-type noise; and such clippers were found in all the sets listed above except the BC-639-A. The vulnerability of these receivers to c-w and to a-m signals was much greater than was that of the receivers in group (1), but it was suspected that the cause was random instability in the jammers at these frequencies. This hypothesis was verified by tests on one of the receivers in group (1) (the ARB), using a special signal which consisted of continuous wave frequency-modulated to a very small degree by four tones of about 200 c and one of approximately 500 c, the maximum deviation in no case being more than 500 c. This signal jammed the ARB receiver at a J/S ratio somewhat less than 0 db, which is similar to that observed on the v-h-f sets. The jamming effectiveness was 20 per cent at a J/S ratio of —17 db.[279]

An additional study was made of the AN/ARC-1. Several modifications were suggested to reduce the noise in the set at low signal levels. It was found that the excessive noise was caused by overly rapid AVC action in the r-f stage.[282]

Group (3): High-Frequency Frequency-Modulated Receivers

The receivers tested under group (3) were the BC-603-D,[258] the SCR-609-A,[259] and the

SECRET

SCR-300-A.[263] Pulse and wide-sweep f-m signals were found relatively ineffective against these f-m sets, because of the inherent limiting which is a part of the f-m system. Jammers using frequency modulation with bands comparable to the receiver pass band were as effective against these sets as against a-m equipment. Jammers with c-w and a-m signals were also effective, although careful tuning of the receiver helped to improve reception. The effectiveness of these latter types of jammers against f-m equipment was due to a "capture" effect associated with f-m communication. Various methods of eliminating this effect were investigated and reported.[257, 278] It was found that a gain of 18 db to 30 db (depending upon the position of the jammer in the pass band) could be obtained by the installation of an automatic back-biasing arrangement, to be switched in when such interference was encountered.

Group (4) : Very-High-Frequency Frequency-Modulated Receivers

Two sets of this type were studied. The first of these was the AN/TRC-1, which exhibited characteristics very similar to those of the group (3) receivers, particularly as regards vulnerability to c-w and a-m signals.[261] The four audio channels of this multiplex system provided a means of reducing the effect of jamming due to audio masking, in cases where the audio interference was concentrated in a limited portion of the audio spectrum.

Facsimile and teletype were in general more vulnerable than voice systems (but see Section 9.5). The second set studied in group (4) was a facsimile system[90] in which a relatively narrow-band a-m receiver was used in conjunction with a wide-band f-m transmitter modulated by a black and white picture signal. The receiver detected a pulse each time the f-m signal swept through its narrow pass band; thus, in effect, only the edges or transients of the original picture were recorded. Studies were made using both audio and radio frequencies. The results indicated that the loss in detail inherent in this "Transient System" was not counterbalanced by the improved signal-to-noise ratio. That is, the best compromise obtainable compared unfavorably with existing methods. Moreover, the Transient System required very precise background operating adjustments.

In addition to the above, some tests were made on the AN/TRC-8. Vulnerability measurements could not be made on it for lack of test equipment covering the frequencies near 250 mc where it operates, but sufficient information was obtained to indicate that the results of such tests would not be substantially different than for the other voice f-m receivers.[285]

Group (5) : Pulse Systems

This group includes all the pulse communication systems in use by the Armed Services (see Section 9.2.4). The initial susceptibility study was made on the AN/TRC-5 system.[116] The power required to produce jamming in this set was determined for a pulse jammer using several values of pulse length and frequency. The most effective jamming occurred at a pulse rate near 10 kc with pulse lengths of 1 or 2 μsec. Measurements were also made of the jamming power required with continuous wave and with a wide-band fluctuation noise spectrum. The results of these measurements were applied in a calculation of coverage to find the distances and angles over which a jammer with 100-w radiated power could produce interference on a radio circuit set up for maximum link distances. In general, it was concluded, the jamming source would have to be airborne and situated within a narrow range of angles, so that it would be difficult for an enemy with inferior air power to jam the system effectively over any appreciable length of time. Means for possible AJ measures were studied.

Some experiments were made on an arrangement to demodulate a selected channel of a time-division multiplex signal, such as that of the AN/TRC-5. This method used a photocell pickup from the image on a cathode-ray oscilloscope. The pip of the desired channel excited the photocell through a suitable mask on the oscilloscope, and, after proper amplification, an audio signal resulted. The frequency characteristic of the fluorescent screen was such that the higher audio frequencies were greatly reduced, and consequently a high degree of compensation was needed in the audio amplifier.

The system resulted in an audio signal with a

noise level which was fairly high but reasonably intelligible when used in conjunction with a 5-in. laboratory oscilloscope having fairly good brilliancy. The system was unworkable with the image obtained on the oscilloscope of the AN/APA-11 radar indicator assembly, because of insufficient light intensity.

GROUP (6) : SPECIAL SYSTEMS

Several AJ modifications to standard sets, which might be considered under this head, are discussed briefly above in conjunction with the unmodified sets. Other special AJ systems are described in Sections 9.5.2 and 9.5.3.

In addition to these studies, vulnerability tests were made on the receiver AN/TRR-2 as operated by the transmitter AN/TRT-1 for the purpose of selective mine detonation.[283] The set was found to be extremely susceptible to any simple jamming action, because it involved the use of tone selection and impulse keying combined with a superregenerative receiver. The jamming would not be expected to cause false operation but could prevent operation when required.

9.3.3 Conclusions and Recommendations

The results of the tests made to date on all equipment show that there is no universal palliative to make sets less vulnerable to jamming signals of all types. This fact is due to the nature of the intelligence to be conveyed. In addition to the actual existence of the complex transient, the general character must be preserved; it is therefore impossible to discriminate against jamming in favor of the desired signal when they are of the same character. On the other hand, the proper use of the limiter and attention to the time constants of the various receiver circuits can make sets less vulnerable to pulse interference, while careful attention to the circuit elements which improve the stability of the equipment as well as its overall performance results in a set which is less susceptible in general.

These results indicate that the continued study of specific equipments would be less valuable than a detailed study of special components, such as converters, r-f and i-f amplifiers, and detectors. It would also be valuable to continue tests on equipment which incorporates design features of an unusual nature, particularly those which are specifically designed to counteract jamming.

9.4 VULNERABILITY OF GUIDED MISSILE AND ALTIMETER SYSTEMS

A number of measurements were made of the jamming susceptibility of guided missile [GM] and radio altimeter receivers. The techniques and test methods used in these studies were similar to those described in the preceding section on communications receivers.

9.4.1 Guided Missile Receivers

A considerable amount of work was done on the testing of typical GM receivers when subjected to various types of jamming signals. Among the types tested were the Azon, Razon, GB-4, AN/ARW-2, AN/SRW-2, and Hs-293 receivers. The last of these was a German equipment.

REMOTE-CONTROL SYSTEM

The AN/SRW-2 (XA-1) receiver forms, in combination with the AN/ARW-33 (XA-1) transmitter and associated channel multiplication equipment, a remote-control system for guiding distant objects and performing certain other functions. An investigation was made of the vulnerability of this receiver to jamming.[287]

The results showed that the equipment was extremely vulnerable to c-w jamming, because the control signals are tones which must be selected by filters in the receiver. It was also found to be highly susceptible to pulses; certain modifications which were tried, however, improved the operation against pulses a great deal.

ENEMY GM-CONTROL RECEIVER

During the first months of 1944, jamming tests were conducted on three different mockups of the Hs-293 receiver. The first of these copies was completed when only very sketchy informa-

tion concerning the enemy receiver was available.[312] As more detailed information on the circuits was obtained, the succeeding models were built, each to more accurate specifications than the preceding one. When the third model was completed, most of the jamming tests which had been made on the prior models were repeated on it.

Two general types of experiments were performed in these jamming tests. The first consisted of field tests made with transmitters as the sources of jamming and control signals. The second consisted of laboratory bench tests with signal generators as the sources. In all cases, the jamming criterion used was simply that the first relay in the aileron channel of the Hs-293 receiver be prevented from following the alternations of the control signal modulation.

Of the various possible methods investigated for jamming the Hs-293 receiver, the only one which did not require prohibitive amounts of power was spot jamming with modulation at one of the missile-control frequencies. The following types of jamming, listed in order of decreasing efficiency, appeared to be too inefficient as to power requirements to be practical: (1) 50-kc f-m barrage amplitude-modulated at a missile-control frequency; (2) two jamming signals with a frequency difference equal to the intermediate frequency of the receiver; (3) spot jamming modulated by pulses of short duty cycle and high peak power; (4) mechanical f-m barrage at a random frequency; and (5) unmodulated spot jamming.

Enemy Tank-Control System

A comprehensive study was made of the radio control system of a captured German BIVb tank.[314] It was found possible to work out the control system of this tank in quite complete detail (see also Chapter 15).

9.4.2 Frequency-Modulated Altimeters and Bombsights

The vulnerability of f-m radio altimeters and bombsights was estimated on the basis of laboratory tests conducted with four equipments, the U.S. AN/ARN-1 and AN/APN-1 altimeters, the German FUG.101 altimeter, and the U. S. AN/APG-4 low-altitude bombsight.

Radio Altimeters

A study was made on the jamming susceptibilities of the three f-m radio altimeters listed above.[321, 331] In the laboratory it was possible to determine the amount of jamming signal required at the altimeter receiving antenna to cause the unit to be jammed. The very important problem of antenna patterns and the merits of various jamming locations could not be investigated properly without full-scale tests in the field.

In spite of the protection against modulated jamming signals provided by the balanced detector in the American altimeters and the square law detector in the FUG.101, it was found that the most effective interference was a sinusoidal a-m carrier tuned to within 25 mc of the center frequency of the altimeter transmitter. The reading of the altitude indicator in one of these f-m altimeters was determined by the frequency of the audio beat which resulted from mixing the transmitted signal and the delayed ground echo. To override this audio voltage, therefore, and cause the altimeter to indicate an erroneous altitude, the audio modulation on the jammer had to be fixed at the frequency corresponding to the erroneous reading desired.

In general, two types of altimeter jamming were considered. The first was the jamming of low-flying aircraft or of guided missiles dependent on a radio altimeter to maintain them at the desired low altitude.[321] In this case it was best to make the altimeter indicate a higher altitude than correct and thus possibly cause the plane or missile to fly into the ground or water. The laboratory measurements showed that to accomplish this result the jamming field strength at the altimeter receiving antenna had to be approximately 5 times the echo field strength there for the American altimeters, but only 1.5 times the echo for the FUG.101. These figures were based on an aircraft flying at an original altitude of 100 ft.

A second type of jamming was required when the altimeter was used as a proximity detonating device in large missiles[331] (see Chapter 10).

In this case, it was desirable to cause the altimeter to read low as the missile approached its detonating altitude, thus producing a premature explosion. It was found that such "downward" jamming required considerably more jamming power. To jam an altimeter down to a reading of 100 ft when the instrument was flying at an altitude of 1,000 ft required a jamming signal strength about 400 times the echo signal strength in the altimeter receiving antenna, in the case of the American altimeters, and about 16 times the echo, in the FUG.101. In general, the FUG.101 was found to be considerably more vulnerable than the American altimeters; but even with its comparatively high vulnerability, the power necessary to jam the FUG.101 (assuming simple antenna patterns) varied from several hundred to many thousand watts.

Vulnerability of Bombsight

An investigation was made of the vulnerability of the AN/APG-4 low-altitude f-m bombsight. In the laboratory, measurements were made to determine the relative effectiveness of jamming signals and the amounts of such signals required to cause failure of the APG-4. It was found that the most effective jamming was produced by a carrier, amplitude-modulated at about 3,000 c and tuned to within the f-m band of the APG-4 transmitter. The same jamming signal was found to be only slightly less effective if detuned as much as 40 mc from the APG-4 center frequency. The unmodulated jamming carrier was found to be considerably less effective and indeed had no jamming effect unless tuned to a frequency within the 5-mc f-m band of the APG-4.

Full-scale jamming tests were conducted against a corner reflector. The AN/APG-4 was installed in an airplane and provisions were made for the continuous recording of the amplitudes of the echo and jammer signals. In this manner, the jamming power required was measured as a function of echo field strength. The use of various types of jamming signals verified the laboratory results.

In order to estimate the jamming power that would be required in the case of real ship targets, the echo amplitudes were measured for several naval vessels. By comparing these measurements with those made on the corner reflector it was possible to assign jamming power requirements to each vessel. It was concluded that a jamming power of 100 w might be required in the case of the largest vessel, assuming that a simple half-wave antenna was used for the jammer.

9.5 RADIO-PRINTING SYSTEMS

Studies were made on a variety of types of printing systems, to determine and improve their AJ characteristics. On the basis of the results of these investigations, improved systems were developed which were sufficiently good from the AJ standpoint to be used as substitutes for voice or code systems, when the latter became jammed to such an extent as to be useless.

9.5.1 AJ Characteristics of Teleprinters

A research project was established to investigate the AJ characteristics of five- and seven-unit printing telegraph systems and to devise means to improve their performance when jammed.[91] Susceptibility tests were run on two basic systems; namely, the five-unit start-stop teletype system and the synchronous seven-unit RCA error-detecting system. Four types of noise were utilized: (1) sawtooth impulses; (2) square-wave impulses; (3) random keyed tones; and (4) fluctuation noise.

It was found that the last was the least effective for jamming on all systems. Square-wave impulses were the most effective against a d-c signal, and a square wave keyed audio tone was the best against tone signals when the interference tone frequency differed from the signal tone by the keying rate. The most satisfactory circuit arrangement for combating jamming conditions includes: (1) space-diversity reception; (2) two-tone f-m keying; and (3) seven-unit operation employing synchronous transmission, with front-end correction and collation.

Against fluctuation noise, a two-tone five-unit

start-stop teletype system combined with space diversity has a 26-db signal-to-noise improvement over an on-off keyed single-receiver amplifier-rectifier five-unit start-stop teletype system. Synchronous regeneration will add 5.5-db improvement. If the five-unit start-stop printers are replaced by seven-unit radio printers with collation, an additional 1.5 db can be realized.

9.5.2 Impulse and Time Code Systems

An investigation was made of the AJ characteristics of the British Beechnut system. The results led to the development of an improved system of the same type known as Voflag.

Vulnerability of Beechnut

Beechnut was a ground-to-aircraft communication system employing two-tone keying to set up a message before the pilot on a display which consisted of six ideograms. The British Beechnut equipment used two superaudible frequencies.

Jamming tests were made on a complete Beechnut system, including the standard r-f transmitting and receiving equipment used for ground-to-aircraft operations.[98] The interference was introduced at the receiver input. It was found that this system was jammed effectively by interference with one-half the amplitude of the desired carrier, if the jamming carrier was 100 per cent modulated by a superaudible tone approximately equal to the frequency of the transmitted "marking" tone.[106] A similar type of interfering signal jammed the aircraft-to-ground acknowledgment signal when the interfering carrier was only one-tenth of the desired signal.

Development of Voflag

In order to overcome some of these difficulties, a two-tone system using a six-element error-proof code of well-known characteristics was developed. This system was known as Voflag. It was found that the Voflag system could be jammed effectively by a jamming carrier of one-half the intensity of the desired carrier if it was 100 per cent modulated by an audio tone approximately equal to the frequency of the transmitted marking or "spacing" tone. The error-proof code, however, was so arranged that an automatic answer-back was provided from the aircraft to the base station indicating "message O.K." or "received with errors." Manual acknowledgment was also provided for use when the pilot had carried out instructions.[117] Another version of Voflag printed the ideograms on a record slip instead of displaying them before a pilot.

At the end of World War II, no units had been delivered, nor had the design of the printer attachment been completed. These jobs were finished, however, before work on the development ceased.

9.5.3 AJ Printing Attachment

A research project was established with the aim of protecting radio communications equipment against jamming by means of an auxiliary apparatus, which could be added to existing voice sets without modifying them, and which could be operated by unskilled personnel.

Equipment Developed

An airborne equipment weighing 41 lb was evolved, which consisted of a typewriter-like keyboard for sending, together with a tape printer for receiving. The operating speed was fixed at ten words per minute. This slow-speed radio printer could receive messages through noise-modulated interference 11 db stronger than the wanted signal. This J/S ratio was an improvement over voice communication by about 14 db; that is, about 25 times the jamming power was required to jam the printer as was needed to jam voice.[164-166]

Basic Method. The printer signal consisted of a-f tones, which were introduced into the microphone jack of the voice transmitter. At the receiver, the signal was taken from the earphone jack. Because of the slow speed of operation (ten words per minute) the bandwidth required for the printer-signal tones was quite narrow, about 20 c. During jamming the audio output of the receiver contained additional frequency components, whose energies were generally spread over a much wider audio band-

width. Consequently, when the desired printer-signal tones were selected by means of narrow-band audio filters, much of the jamming energy was eliminated. This method was the only one which was considered to be capable of protecting voice radio systems against jamming without modification of the existing equipment.

On the other hand, the method was quite vulnerable to jammer modulation consisting of audio tones of the proper frequencies, or to jamming by captured equipment. In consequence, the printer-signal tones had to be scrambled prior to transmission and unscrambled in the receiver. The enemy would thereby be forced to spread his jamming energy over a greater bandwidth, with a corresponding reduction in effectiveness. The synchronization and phasing of the frequency scrambling-descrambling operation requires a certain degree of skill; provision was made, therefore, to switch this feature out of operation when necessary.

Effectiveness of Method

When a jamming signal consists of modulation which is uniformly distributed over a given frequency bandwidth, the energy in any portion of that bandwidth is directly proportional to the width of the portion under consideration. If the signaling speed is reduced, therefore, and the audio bandwidth is decreased proportionally, the effective power of the interference is likewise reduced in direct proportion. This relationship holds on either an a-f or an r-f basis, depending on whether the selective circuits are in the audio or the r-f stages.

In this development, inasmuch as 20-c r-f selectivity could not be obtained without drastic modification of the existing voice sets, it was necessary to utilize a-f selectivity, but over a relatively wide-band r-f link. It was found that under these conditions the strong jamming carrier interfered with the normal demodulation of the desired signal sidebands, as a result of which the wanted signal was appreciably suppressed in the audio output of the receiver. A study of this "apparent demodulation" phenomenon was made[106] and moderate success was achieved in the minimizing of its severity.

An approximate rule is that when a-f selectivity is used on a signal which is transmitted over an r-f link subjected to jamming, the minimum effective r-f J/S power ratio varies inversely as the two-thirds root of the audio bandwidth. In other words, if the signaling speed be reduced, say, from 80 to 10 words per minute (and the audio bandwidth in proportion), it becomes possible to operate through interference whose power is four times as great as formerly. This example makes it clear that still further antijamming protection could be achieved only at the expense of very low signaling speeds. Accordingly, 10 words per minute was selected as a practical minimum speed.

Details of Printer

Since the printer was expected to operate through conditions of jamming, special precautions were taken to insure satisfactory operation during normally marginal conditions.

Protection against fading was achieved by the frequency-shift system of mark-space keying, in which one audio tone was transmitted for marking, and another audio tone was transmitted for spacing; this gave very satisfactory results. A single-case printer was employed, because of the risk that temporarily successful jamming might leave the printer in the wrong case. An error-protected printer code was employed, so that, should the jamming manage to mutilate the signal, an error symbol would be printed in lieu of an erroneous character. This protection greatly improved the reliability of the printer, since mutilations were apparent at a glance and the mental effort of inspecting the test and correlating it with the confirmation was eliminated.

Although a stop-short printer would have been preferred, it was not used because momentary jamming could then throw the printer out of step for quite a number of characters. The printer was therefore designed for synchronous operation; for this purpose a special tuning fork was employed, with a frequency stability of about one part in a million over a wide temperature range. This fork was sealed in a partial vacuum so that its rate would be unaffected by the low atmospheric pressures encountered at high altitudes. A special synchronous motor was developed, which provided the required power at a very low cost of size, weight, and power con-

SECRET

sumption. The synchronous operation was applied to advantage to obtain optimum regeneration of the received signal and to synchronize the scrambling-descrambling operation.

Many functions of the printer were performed electronically, rather than mechanically, and the resulting mechanical simplification is such that little tool-up time should be required for production of the printer. The printing-head and keyboard were designed as a compact unit, which could be located in the aircraft cockpit and connected to the main control unit by interconnecting cables.

The above features contributed to an inherent operational simplicity and reliability suited to the type of military service for which the printer was designed. At the same time, two basically different types of secrecy were provided, and a third form could be added at very little cost, so that the printer is as much a secrecy device as it is an AJ attachment.

Recommendations

The equipment developed on this project is about the best solution foreseen for applications where the given limitations still apply. It could be added to any voice system at any time; and, by its addition to a-m or pulse-modulated voice systems, the communication link would be enabled to operate through stronger jamming, to about the same extent as could be accomplished by using c-w operation with highly trained telegraphists for the purpose. It is conceivable that this equipment, used with voice transmitters, might be considered as a satisfactory substitute for c-w telegraphy.

It is believed, however, that any peacetime program to achieve protection against jamming should not be concerned with the type of equipment already in service, but should be permitted an unrestricted field of development. Speed of communication should not have to be sacrificed in order to achieve AJ protection. Printers (when used) should function at high speed, with skilled keyboard operators. Preferably, however, voice communication should be used, allowing for speed without skilled operators. Possible methods for achieving these results include r-f carrier frequency scrambling and time modulation of pulses with time scrambling.

PART IV

RADAR APPLICATIONS

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Chapter 10

RECEIVING AND DIRECTION-FINDING EQUIPMENT FOR RADAR COUNTERMEASURES

10.1 INTRODUCTION

THE NEED FOR search and direction-finding [DF] facilities has been discussed in a general way in Chapter 1. The detailed discussion of such devices can be subdivided into a consideration of the design requirements of such equipment, the fundamental technique developments necessary for the realization of these design requirements, and finally a description of the various receivers, direction-finding equipments, and associated devices which have been found necessary for an effective radio countermeasures [RCM] program. All of the important technique developments which grew out of this program are covered in detail in the accompanying monograph,[809] so this chapter is devoted to a consideration of the design requirements and a description of the equipments actually developed for military use.

The majority of this work was done by the Radio Research Laboratory (under contract OEMsr-411). Some of the early work was done, however, by the Columbia Broadcasting System (under contract OEMsr-867). There was also a considerable amount of activity in this field, of course, by various Service laboratories (especially in connection with the development of pulse analyzers and other indicating equipment) and by the several manufacturers who did production engineering on these devices.

10.2 DESIGN CONSIDERATIONS

The myriad tasks which RCM receiving and DF equipments are called upon to perform demand either a single relatively complex and complete equipment, a basic equipment with a considerable number of attachments, or a collection of simple equipments, each of which performs a relatively small number of jobs. All three of the above solutions to the overall problem have been tried, and all are successful. The choice under a given set of conditions must be made on the basis of a careful analysis of the problem at hand. The following general considerations concerning each of the principal functions of such equipment may be of aid in understanding the reasons for the specific designs discussed later in this chapter.

10.2.1 Analysis of Enemy Radar by Use of Search Receivers

Search receivers, when supplemented by suitable indicating and analyzing devices, can be instrumental in obtaining much valuable information concerning enemy radar equipment. Some of the operating characteristics that may be determined by searching, the reason for their importance from a countermeasures viewpoint, and the probable range of values that will be encountered are as follows:

1. *Carrier frequency* (about 50 mc and higher). In order to permit intelligent design and successful employment of countermeasures devices, it is important to know the exact operating frequency of specific radar systems and the band of frequencies over which the radar sets of a given type are spread.

2. *Antenna polarization* (horizontal, vertical, or rotating). Since it is important that the transmitter power available for jamming purposes be used as effectively as possible and since the maximum possible sensitivity is generally desired in receivers, it is essential that the polarization of the enemy emissions be ascertained and the jamming transmitter and search, warning, or DF receiver antennas be arranged accordingly.

3. *Lobe-switching rate* (from about ½ to 500 per second). An accurate knowledge of the lobe switching (or split rate) of enemy systems is of importance in the design and application of certain types of deception devices, for example, Peter. More detailed information is given

in Chapter 12. This can be readily determined where lobe switching of the radar transmitter is practiced.

4. *Maximum range* (from a small fraction to hundreds of miles). The maximum range for which a radar system is *designed* may be estimated from a knowledge of the pulse-repetition frequency (prf ranges from about 20 to 5,000 pulses per second). In the case of an oscillating or rotating searching beam the *actual* maximum range may be ascertained for a specific target when the beam stops searching and locks on the target. Knowing the maximum range of a radar is important, since, in general, it is not desirable to operate jamming transmitters until they come within range of the radar system.

5. *Minimum range* (from tens of yards to a few miles). The minimum design range may be estimated from a knowledge of the pulse length (from about 0.1 to 25 μsec) and the pulse shape. Information as to the minimum range of an enemy radar system is not of particular interest from an electronic countermeasures viewpoint but it may be of considerable value to other operational branches of the Armed Services and to the designers of our radar equipment. Information concerning the pulse shape, however, is of importance in the design of certain deception devices (see Chapter 12).

6. *Equivalent radiated power.* Field intensity measurements, coupled with information as to the distance from the radar at which the measurements were taken, will permit an accurate estimate to be made of the equivalent radiated power of the radar and of the necessary sensitivity of warning receivers.

7. *Rate of rotation* (from about 0.1 to 100 per minute). The probable rate of rotation of a radar is of considerable interest in the design and application of automatic search receivers since it influences the selection of the rate at which the receiver scans the frequency spectrum. Furthermore, observations made on the rate of rotation are useful in determining whether a plan-position indicator [PPI] is used by the radar under surveillance.

8. *Resolution or directivity.* Information concerning the directivity patterns in the horizontal and vertical planes will indicate the resolution or directivity of the radar and provide an estimate of the antenna gain. Information about the vertical pattern may also reveal nulls or blind spots which may be used to advantage in approaching the radar in question.

10.2.2 Analyzing and Indicating Equipment

It is evident from the foregoing that, in addition to the search receiver itself, there is need for various associated analyzing, recording, and indicating equipment if full advantage is to be taken of the emission from a radar system in obtaining information relative to its operating characteristics. The auxiliary equipment includes frequency meters, pulse analyzers, cathode-ray oscilloscopes, and audio oscillators.

The accuracy of frequency meters for the radar portion of the frequency spectrum is, in general, not sufficiently great to permit the setting of jamming transmitters by reference to the stated absolute frequency. It is preferable to set such transmitters on frequency by employing the same frequency meter as was used originally to determine the enemy radar frequency. Although the absolute calibration of such instruments may not be so accurate as desirable, their stability and relative calibration may be satisfactory if they are used first to determine the frequency to be jammed and then to set the jammer to this frequency.

Spot-jamming operations (see Chapter 11) demand a high degree of accuracy in setting jamming transmitters on frequency. The most practical method of doing this has been found to be the simultaneous reception of the signals of the radar to be jammed and of the jammer. This may be done aurally with any receiver with small enough bandwidth, sufficient dynamic range, and satisfactory discrimination against spurious signals. It may also be done more conveniently by using a receiver provided with panoramic presentation of signals. Provision of panoramic presentation may actually simplify the design of a receiver by making it easy to identify spurious signals, thus eliminating the necessity of designing the receiver so as to reject them. Panoramic presentation certainly makes the monitoring of the jammed signal easier, since the variations in signal strength,

attempts at detuning, etc., may be observed immediately, both as to magnitude and direction. In general, panoramic presentation makes jammer frequency setting and monitoring easier and more accurate. Provision for panoramic presentation may be made as a part of the receiver design or as an attachment for many types of standard search receivers.

10.2.3 Automatic Search Receivers

Radar reconnaissance, for reasons already mentioned, is frequently done from aircraft. The task is not particularly simple even though the geography may be such that the searching craft is able to stay out of range of the radar under investigation. For example, in an area where there is only one radar (or very few) operating on an unknown frequency, it is necessary that there be a double coincidence if the signal is to be heard; that is, the search receiver must be tuned to the radar frequency at the instant the radar is oriented toward the search receiver.

Since radar and similar types of emissions (such as for radio-controlled glide bombs or tanks) may take place anywhere in a very wide band of frequencies, searching becomes a very tedious job if it is undertaken in a thorough manner. At low radar frequencies this is not so serious a problem as at high frequencies since, in the former case, the directivity of the radar transmitting antennas is not so great as at high frequencies. Furthermore, at low radar frequencies there are often spurious side lobes of radiation that emit sufficient power to permit reception on a sensitive receiver even though it may not be in the main beam of the radar.

At high radar frequencies the search problem is doubly difficult, since not only are the beams generally extremely sharp and possessed of only very minor spurious lobes, but also there is a much larger number of possible channels. On the other hand, if the reconnaissance is over an area where there are a large number of radars operating, it may be difficult, because of the speed of flight and the number of radars involved, to record and distinguish between all the radar signals heard.

The various types of automatic tuning and recording means that have been devised to alleviate these difficulties are described on the following pages. In some instances, these devices are such that they can be carried on regular bombing missions (operating without attention) and thus provide preliminary data concerning enemy radar. In general, however, automatic devices do not record the operating frequency of received emissions with sufficient accuracy for the presetting of jamming transmitters. Rather, they are useful for indicating the general whereabouts, both in frequency and geographical location (by comparing the time of signal reception with the flight log), of the radar stations heard. A detailed search with more precise measuring equipment can then be made with the minimum amount of effort.

10.2.4 Sensitivity of Radar Search Receivers

It is not generally necessary that radar search receivers have the extreme sensitivity which is desirable in communications receivers or in receivers that are a part of a radar system. This is true because of the extremely high field intensities that exist at the search receiver location when it is within range of a radar. This fact is obvious when it is recalled that only a small portion of the total energy intercepted by the target is returned to the radar and yet this echo must be sufficiently great to permit the reception of a discernible signal by the radar receiver. The warning receiver, on the other hand, is exposed to the intense field that exists at its location whenever the radar beam is oriented in that direction.

Sensitive radar search receivers are useful, however, since they will permit the reception of radar signals at maximum distances. Furthermore, with a sensitive receiver, radar emissions will be observable even though the radar involved may not be "looking" directly toward the receiver.

10.2.5 Radar Warning Receivers

The desirability of knowing, under many circumstances, when one is being observed by radar of a certain type led to a serious study

of the possibility of using radar warning receivers. Under some circumstances (e.g., submarine operations), it is feasible to use standard search receivers for obtaining warning. This type of operation, although it has proved to be of the utmost importance, needs no further discussion. It is sometimes necessary, however, to develop special receivers for radar warning, especially if the receiver must operate unattended and give warning only when actual danger exists and proper evasive action or other measures must be taken.

Although the basic idea of a radar warning receiver was that of a simple device, experience has shown that to be useful the receiver must be capable of rather complex operations. This was particularly true in the European Theater of Operations. In this area the enemy searchlight-control [SLC], gun-laying [GL], and ground-controlled-interception [GCI] radar were all in a narrow band of frequencies and enemy aircraft-interception [AI] and coastal-watch equipment were similarly disposed in adjacent bands. To be of maximum usefulness, a warning receiver has to be able to discriminate between these different types of radar, since different evasive tactics are practiced against the various types.

The time that may elapse before evasive action must be undertaken is different for variout types of radar. For example, evasive action against GL need not be taken until after the enemy radar has been centered exactly on the target for a period long enough to supply sufficient data to the antiaircraft predictors to permit accurate firing. Thus, GL warning devices might include means for determining when this centering takes place and in addition introduce a time delay of something less than a minute (since all predictors require a flow of uninterrupted information for a certain period of time) before giving a warning signal.

In the case of GCI, a warning need not be given until the target has been under surveillance for 5 min or thereabouts. For AI warning, however, the warning signal should be given whenever the AI-equipped aircraft is almost close enough to press home the attack. Unless arrangements are made to provide these distinguishing features, the warning equipment, at least in a congested area, will give almost continual warnings which, if heeded, would result in an intolerable amount of evasive action.

Warning receivers for the early-warning [EW] radar frequencies are not required, as a rule, since attacking aircraft must fly over the EW radars in any event. However, in theaters where the location of every EW equipment has not been ascertained by prior search—i.e., in initial raids into new territory—the use of warning receivers for the EW bands may be useful in indicating when one first comes under scrutiny and when interception may be anticipated.

The above considerations resulted in the development of several radar warning receivers, but, because of the rapidly shifting tactical situation and necessary delays encountered in placing equipment of this kind into production, none of these received extensive operational use. The British, on the other hand, did manage fairly early in World War II to get one warning receiver (Boozer) into fairly widespread use. The effectiveness of such devices is difficult to ascertain, since a good part of their value may be due to their effect on the morale of the users, especially if they make it possible for the operators to relax except in times of actual danger. At any rate, the various developments of this type are described later in this chapter, so that the reader may evaluate for himself the usefulness of such devices under a given set of circumstances.

10.2.6 Homing Systems

By providing a search receiver with suitable directional antennas, switching mechanisms, and indicators, a system can be developed that will assist the craft carrying the equipment to orient itself toward a source of radio, radar, or jamming signals. An installation of this type is known as a homing system, since it will indicate the course to be taken in order ultimately[a] to reach the source of signals. The use of equipment of this kind is more or less confined to

[a] Because of drift, a spiral course will actually be followed unless corrections are made.

airplanes since in larger, slower moving, and less mobile craft the use of DF systems offers several advantages that more than offset their added size and complexity. Direction-finding systems are also applicable to aircraft. They bear a relation to homing systems similar to that which the turret guns bear to the fixed guns on the airplane. With a homing system or with fixed guns the airplane must be turned toward the target, whereas with a DF system or with turret guns the airplane may fly a chosen course while still coming to bear upon the target.

Homing systems are most useful to airplanes or guided missiles that wish to attack a source of signals. For example, they can be of considerable assistance to low-flying aircraft intent upon attacking an enemy radar station. Although the location may be precisely known, when the plane is flying at low altitude it will seldom be possible to see the station until the aircraft is almost over it. Homing equipment should assist materially in keeping the aircraft headed toward the target.

Another application is the locating of airborne jammers or of radar-carrying aircraft for the purpose of attack. In this application, homing methods have the advantages over AI radar that they require less elaborate equipment and that they do not provide any radio warning to the enemy, even if he is equipped with warning receivers.

In the selection of homing equipment for a specific application it is exceedingly important to bear in mind the need for using an antenna system whose polarization corresponds to that of the transmitter. Thus, if the source of signals is an antenna having vertical radiating elements, a vertically polarized antenna should be used for the homing system if erroneous results are to be avoided. It should also be noted that most directional antenna systems operate properly only over a limited band of frequencies, since the problem of providing a broadband directional system is a very difficult one.

Homing equipment has not been found to be of any great practical value for radio and radar reconnaissance undertaken for the purpose of locating enemy installations. In operations of this type, it is necessary to turn the homing-equipped craft toward the target in order to determine its bearing and to repeat this operation from two or more locations. With aircraft this procedure causes the reconnaissance plane rapidly to approach dangerously close to the enemy installations. Furthermore, it is time-consuming because of the need for orienting the craft, first one way and then the other, to make certain it is on the correct heading. This operation often results in considerable doubt concerning the result, particularly if the radar signal is waxing and waning as it scans back and forth. Thus the use of homing systems for spotting the locations of enemy installations, while possible, cannot be recommended. The use of a DF system is preferable for this purpose.

10.2.7 Direction-Finding Systems

A radio DF system differs from a homing system in that the direction from which a signal is arriving may be determined directly from the indications of the direction finder. Equipment of this type is useful not only in aircraft but also in ground and sea-borne craft or in fixed ground-based installations.

With a radio direction finder the direction toward a source of signals (radio, radar, or jamming) may be ascertained without requiring the vehicle carrying the equipment to deviate from a prescribed course. Direction-finding equipment, while more complicated than homing equipment, does not necessarily require more skill for its operation; the reverse may, in fact, be true in some instances.

As with homing equipment, the polarization of the antenna of a direction finder should be the same as that of the transmitter antenna. In the more elaborate systems, provisions are made to obtain proper response from vertically, horizontally, and circularly polarized waves.

10.3 EQUIPMENT DEVELOPMENTS

Most of the receiving and DF equipment developed by Division 15 for radar intercept employed more or less standard designs,

although the techniques used[809] to achieve the desired results were somewhat novel. In other words, the receivers employed either standard superheterodyne circuits or in some cases used direct-detection circuits with crystal detectors. The design of the various mixers, oscillators, preselectors, i-f amplifiers, etc., for the receivers, however, involved radical departures from the conventional type of design because of the higher frequencies involved and the larger frequency coverages obtained. Since the various technique developments have been discussed elsewhere,[809] this section will be devoted to comments concerning unusual features of the receiving and DF equipments listed in Tables 1 and 2.

10.3.1 Search Receivers

Most of the search receivers shown in Table 1 employ standard superheterodyne circuits. Because of the very high frequencies involved, r-f amplification before the mixer is not employed, since the amplifiers available at the time of the development of the receivers did not allow an improvement of signal-to-noise ratio by this means. Some of the receivers, however, do employ selective circuits before the mixer to eliminate image and harmonic responses. The mixers employed are diodes for frequencies below a few hundred megacycles and crystals for the higher frequencies. The i-f amplifiers are generally very wide band (10 to 20 mc) to improve the probability of intercepting sweeping signals. Most of these receivers are equipped with video output channels (for use in conjunction with pulse analyzers and other similar equipments) and panoramic adapter outputs in addition to regular aural output. Some of the receivers include provisions for narrowing the i-f amplifier bandwidth to allow use of the receiver for setting jammers to frequency. A general design feature of most of the receivers is the provision of interchangeable tuning units for various frequency ranges. These tuning units contain preselection filters, the local oscillator, the mixer, and sometimes one or more stages of i-f amplification, while the remainder of the receiver contains all the other circuits.

It will be noted that two direct-detection receivers are listed. In view of the comments in Section 10.2.4 it will be seen that these receivers can be quite useful for most radar intercept work, since the signal strength encountered is generally quite high. One of these receivers employs a rather novel presentation system (including a tape and a panoramic dial) described elsewhere.[809]

One receiving system which incorporates virtually all of the best design features available to date (Type D-9000) will be described as an example of the type of equipment developed. The receiving equipment (see block diagram in Figure 1) consists basically of antennas for three functions, the several units of the receiver which were mounted in a single receiver console, and a Type DBM-1 direction-finding unit.

As shown in the diagram, each antenna is connected to the receiver through an antenna and video switching unit. The r-f switches in this unit are operated by remote control and select specific antennas to be connected to each of the two separate receiving channels. This feature permits operation of one receiver as a monitor while searching is being done with the other receiver.

The receiver uses a standard superheterodyne circuit. The preselector and mixer, together with the first few stages of i-f amplification, are housed in the tuning unit, while the remainder of the circuits are housed in the presentation unit. This presentation unit consists of an i-f amplifier (for further amplification of the 200-mc i-f signal from the tuning unit), a detector, a video amplifier, a panoramic-presentation unit (which operates by sweeping a narrow-band receiver across the i-f amplifier output), and a pulse-analysis unit. The pulse-analysis unit indicates on meters the prf and the pulse width of the received signal. In addition, video output from both presentation units is fed into the switching unit, which provides selection of circuits to feed video signals either to the DBM-1 indicator, for determination of the direction of the signal source, or to the remote panoramascope mounted on the transmitter console of an Elephant jamming system (see Chapter 11),

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TABLE 1. Radar countermeasures receiving equipment.

Identification Nos.	Use	Frequency range (mc)	References	Remarks
Army: SCR-587 Navy: ARC-1	Superheterodyne search receiver.	See tuning units below.	425	Early model receiver superseded by those listed below.
RRL: D-1003 Div. 15: RP-144 Army/Navy: AN/APR-1	Airborne superheterodyne search receiver.	See tuning units below.	650	I-f bandwidth 2 mc.
RRL: D-1003 Div. 15: RP-144 Navy: AN/SPR-1	Ship-borne superheterodyne search receiver.	See tuning units below.		Above receiver converted for shipboard use.
RRL: D-1005 Div. 15: RP-144 Army/Navy: AN/APR-4	Airborne superheterodyne search receiver.	See tuning units below.		I-f bandwidth switch: 4 or ½ mc.
Army: TU-58A Navy: CPR-47-AAF	Tuning unit for above receivers.	100-370	426, 436	Early model; two-dial control.
Army: TU-57A Navy: CPR-47-AAF	Tuning unit for above receivers.	290-950	426, 436	Early model; two-dial control.
RRL: D-104 Div. 15: RP-141 Army: TU-56A Army/Navy: TN-1/APR-1 TN-16/APR-4	Tuning units for above receivers.	40-105	512	Available with single-dial control and either manual, motor-driven, or sector-sweep operation.
RRL: D-101 Div. 15: RP-141 Army: TU-58B Army/Navy: TN-2/APR-1 TN-17/APR-4	Tuning units for above receivers.	75-300	494, 501	Available with single-dial control and either manual, motor-driven, or sector-sweep operation.
RRL: D-102 Div. 15: RP-141 Army: TU-57B Army/Navy: TN-3/APR-1 TN-18/APR-4	Tuning units for above receivers.	300-1,000	494, 513	Available with single-dial control and either manual, motor-driven, or sector-sweep operation.
RRL: D-103 Div. 15: RP-141 Army: TU-59B Army/Navy: TN-3/APR-1 TN-19/APR-4	Tuning units for above receivers.	950-3,300		Manual tuning, two-dial control.
RRL: D-1500 Div. 15: RP-212 Army/Navy: TN-27/APR	Tuning units for above receivers.	1,000-3,100	397	Single-dial control.
RRL: RA-2600 Div. 15: RP-135 Army/Navy: AN/APR-5	Airborne superheterodyne search receiver.	1,000-3,100	489, 536	AN/APR-5A is same as AN/APR-5 except that mixer may be changed to cover 3,000 to 6,000 mc.
RRL: RA-2700 Div. 15: RP-291 Army/Navy: AN/APR-6 AN/APR-5A	Airborne superheterodyne search receiver.	3,000-6,000	536, 641, 664	Can be used with R-1000 variable high-pass filter (see Chapter 4) for identification of spurious responses.

TABLE 2. Radar countermeasures homing and direction-finding equipment.

Identification Nos.	Use	Frequency range (mc)	References	Remarks
RRL: C-1700 Div. 15: RP-106	Antenna and video commutator for homing.	40-3,000	526	
RRL: C-1900 Div. 15: RP-209	Antenna and video commutator and indicator for homing.	Dependent on receiver.	671, 695	Available with either electronic or mechanical commutation. Antennas for horizontal polarization for azimuth only; homing for 100- to 200-mc range also available.
RRL: M-3900 Div. 15: RP-242	Antenna relay plus A-N cam for homing.	Up to 1,000	426	
RRL: C-1600 Div. 15: RP-188 Army/Navy: AN/APQ-14	Homing receiver.	90-130		For use with Pelican or Dragon vehicle as homing bomb.
RRL: C-2100 Div. 15: RP-298 Army/Navy: AN/APA-42 AN/APA-24	Airborne direction-finding system.	100-165 165-275 275-450 450-750	411, 658	Uses Adcock antenna for vertical polarization and dipole for horizontal polarization, mounted as single unit. Heads for various ranges mentioned are interchangeable on most models on single mount. Some of these units have hydraulic drive; others electric drive. Dipole and special converter also available for use on horizontal polarization only for range 50 to 100 mc.
RRL: M-2300 M-3000 Div. 15: RP-298 Army/Navy: AN/APA-17	Airborne direction-finding system.	300-1,000	394, 636	Employs constantly rotating antenna assembly with polar indication.
RRL: M-2600 Div. 15: RP-271 Navy: CXGA	Ship-borne direction-finding system.	300-900	607, 636	Early model ship-borne direction-finding system replaced by revised model listed below.
RRL: M-4100 Div. 15: RP-271 Navy: DBM-1	Ship-borne direction-finding system.	300-1,000	603, 636	Revised ship-borne direction-finding system. Similar to AN/APA-17 electrically.
RRL: M-6200 Div. 15: RP-298 Army/Navy: AS-222/APA-17	Airborne direction-finding head.	65-280	828	For use on horizontal polarization only with above direction-finding systems.
RRL: M-6100 Div. 15: RP-271	Revised ship-borne direction-finding head.	90-1,400	731	For use with above direction-finding systems.
RRL: M-6400 Div. 15: RP-298 Army/Navy: AS-108B/APA-17	Revised airborne direction-finding head.	135-2,100	829	Scaled-down model of above head for airborne use.
RRL: M-4500 Div. 15: RP-271 Army/Navy: AS-186/APA-17	Airborne or ship-borne direction-finding head.	1,000-3,500	382, 636, 661	For use with above direction-finding systems.

TABLE 2. (*Continued*)

Identification Nos.	Use	Frequency range (mc)	References	Remarks
RRL: C-1100 Div. 15: RP-139 Army/Navy: AN/APR-2	Direct-detection search receiver.	90-300 300-1,000	509, 634	Provided with mechanical panoramic indicator and tape recording.
RRL: D-2100 Div. 15: RP-408 Army/Navy: AN/APA-7	Direct-detection search receiver.	1,000-3,500	826	
RRL: K-2000 Div. 15: RP-435 Army/Navy: AN/APR-9	Airborne superheterodyne search receiver.	See tuning units below.		Includes 200-mc center frequency i-f amplifier and other provisions for eliminating spurious responses. Also includes panoramic-presentation unit.
RRL: K-2100 Div. 15: RP-435 Army/Navy: Part of AN/APR-9	Tuning unit for above receiver.	2,000-4,000		
RRL: Q-2100 Div. 15: RP-435 Army/Navy: Part of AN/APR-9	Tuning unit for above receiver.	6,670-10,900		
RRL: D-9000 Div. 15: RP-462 Navy: Part of XMBT	Receiving system for XMBT jamming system.	See tuning units below.		Consists of two separate receiving channels, each similar electrically to AN/APR-9 receiver above, plus additional control and indicating features.
RRL: D-9010 Div. 15: RP-462 Navy: Part of XMBT	Tuning unit for above receiver.	2,000-4,000		
RRL: M-6700 M-6600 Div. 15: RP-271	Airborne or ship-borne direction-finding head.	5,000-12,000	741	For use with above direction-finding systems.
RRL: M-7100 Div. 15: RP-271	Submarine direction-finding system.	2,300-4,600		
RRL: D-9080 Div. 15: RP-462 Navy: Part of SMBT	Tuning unit for above receiver.	6,670-10,900		
RRL: D-2800 Div. 15: RP-462	Unit ship-borne superheterodyne search receiver.	Same as XMBT receiver above.		Consists of single channel of above XMBT receiver.
RRL: A-2100 Div. 15: RP-147 Army: RC-164B	Direct-detection warning receiver.	65-130	505, 548	Single-channel receiver covering frequency ranges given with separate r-f heads.
RRL: R-800 Div. 15: RP-287	Three-channel direct-detection warning receiver.	400-600	368, 417	
RRL: Z-2000 Div. 15: RP-112 Army/Navy: AN/APR-3	Two-channel direct-detection warning receiver.	480-500 510-600		Contains prf discrimination circuits.

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TABLE 2. (*Continued*)

Identification Nos.	Use	Frequency range (mc)	References	Remarks
RRL: D-2200 Div. 15: RP-425 Army/Navy: AN/APA-41	Panoramic adapter.			Operates on 30-mc center i-f amplifier output from standard search receivers.
RRL: R-1600 Div. 15: RP-286	Recorder for search receivers.			Early model superseded by unit listed below.
RRL: D-1800 Div. 15: RP-276 Army/Navy: AN/APA-23	Recorder for search receivers.		398, 676	Operates with standard single-dial search receivers.

so that the transmitter operator may observe the signal and set his transmitter accordingly.

A pair of ordinary tilted-cone antennas (see Chapter 4) are provided for general search use. These are used to provide satisfactory coverage in all directions for both horizontal and vertical polarization. There are also provided four horn-type antennas (monitoring antennas), which are mounted to "look" in four directions, so that each antenna covers a different quadrant in azimuth. The purpose of these monitoring antennas is to pick up the enemy signal while the jamming transmitter is operating. These antennas accomplish this by having considerable discrimination against the transmitter antenna and considerable directivity in the direction from which the signal is being received. In addition, a standard Type DBM-1 DF antenna and indicating unit are provided; these are used to determine the direction from which signals are received.

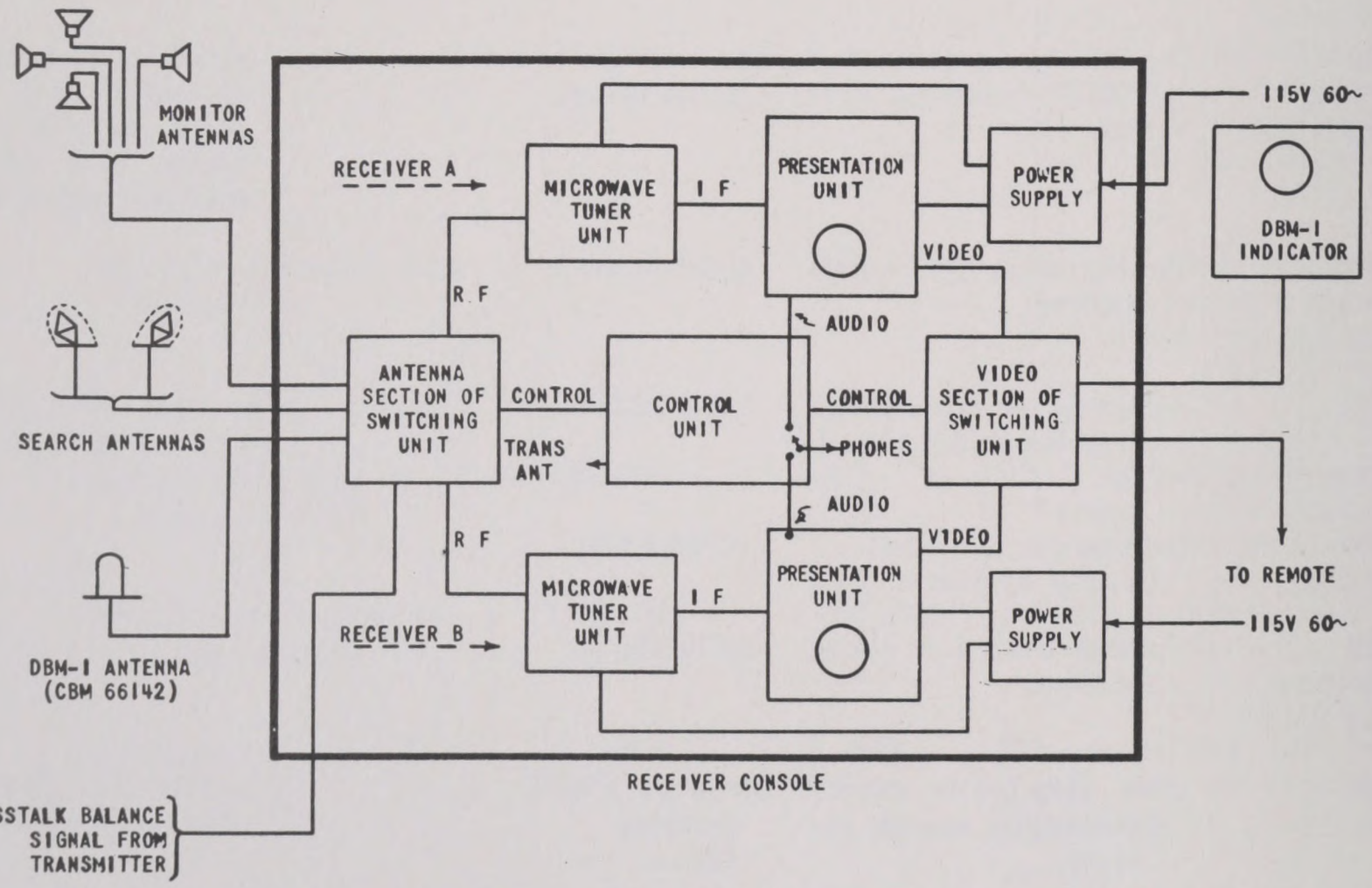


FIGURE 1. Block diagram of receiving section of the Elephant ship-borne jamming system.

10.3.2 Attachments for Search Receivers

The various attachments which have been developed by Division 15 for use with standard search receivers are of quite diverse types; they are also listed in Table 1. Since the techniques involved have been discussed else-

SECRET

where,[809] no further comment concerning such devices appears necessary.

10.3.3 Warning Receivers

The method of operation of warning receivers means that such receivers can be relatively insensitive and can generally be preset to the desired frequency. This means that the r-f circuits in such receivers can, in general, be quite simple. The presentation circuits, which are called upon to discriminate between various prf's and other features of radar signals, may be quite complex. The warning receivers shown in Table 1 are all of the direct-detection type. They consist, in general, of r-f filters followed by crystal detectors and audio or video amplifiers, which deliver their output into various types of indicating systems. Some of the receivers include two or three r-f channels in order to give warning against various radar frequencies.

10.3.4 Homing and Direction-Finding Systems

The various homing and DF systems developed by Division 15 are listed in Table 2. Since these systems have been described in detail elsewhere,[809] no further discussion is needed.

SECRET

Chapter 11

RADAR JAMMING TRANSMITTERS

11.1 INTRODUCTION

RADAR JAMMING transmitters played a very important role in the radio countermeasures [RCM] program of World War II. They accounted for much of the success of the program (along with the use of confusion reflectors described in Chapter 12) and represented the largest single item of expenditure for the program.

The discussion of radar jamming transmitters breaks itself naturally into a consideration of the design requirements of such equipment (which naturally depend to a large extent on the radar employed by the enemy), a discussion of the fundamental technique developments necessary for the realization of these design requirements, and finally a description of the various transmitters and associated developments which were found necessary for an effective RCM program. All the important technique developments are covered in detail in the accompanying monograph.[809] This chapter is devoted to a consideration of the design requirements and a description of the transmitters actually developed for military use.

The majority of this work was done by the Radio Research Laboratory under contract OEMsr-411. Some of the early work was done, however, by the Columbia Broadcasting System under contracts OEMsr-653 and OEMsr-867. The General Electric Company also did most of the development work on one transmitter described herein (Type TDY) under a Navy development contract. There was also a considerable amount of activity in this field, of course, by various Service laboratories and by the several manufacturers who did production engineering on these transmitters.

11.2 GENERAL DESIGN CONSIDERATIONS

Jamming transmitters are distinguished, among other things, by (1) the type of enemy equipment they are designed to nullify; (2) whether they are airborne, ship-borne, ground-based, or expendable; (3) whether they provide barrage or spot jamming; and (4) their effective output power. For this reason a variety of jamming transmitters have been developed, each intended for specific applications. There have even been more than one type of transmitter for a given frequency band, each differing from the others in one or more of the above respects. In many cases it was necessary to undertake the development of new tubes in order to provide means for generating the required r-f energy. This latter work is covered in Chapter 3.

As already mentioned, the success of any RCM activity depends to a great extent upon the skill with which the operation is planned and executed. Intelligent planning, however, requires a thorough knowledge of the virtues and shortcomings of available methods and equipment. Therefore, some of the more pertinent factors that influence the use of jamming transmitters are discussed on the following pages.

11.2.1 Enemy Radar Facilities

Both the Germans and the Japanese were very active in radar development and use during World War II. The German radar facilities have been estimated to have been a two billion dollar investment. The Japanese radar system was less extensive but still represented a sizable portion of their war effort.

Although the radar designs used by the enemy determined the frequency ranges, power output ranges, etc., which received the earliest and most concentrated attention, it was recognized from the beginning that information as to exactly the equipment or tactic the enemy would use next was very difficult to obtain and was always somewhat uncertain. This meant that, while a large amount of effort was necessarily devoted to immediate problems, a pro-

SECRET

gram was initiated to develop a series of jamming transmitters having a wide range of power output and other characteristics for covering the entire radar spectrum. Obviously, those transmitters covering the ranges in which enemy radar was found were manufactured and used in far larger quantities than the remainder of the series; however, the remainder of the series was of considerable insurance value. For the purposes of this book, which is concerned more with a presentation of the "state of the art" than with a historical treatment, these effects are mentioned only to enable the reader to understand the apparently uneven emphasis on various frequency ranges; those interested in details of the enemy equipment may find such information elsewhere.[850]

11.2.2 Communications versus Radar Jammers

Transmitters intended for jamming communications channels differ in a number of respects from those intended for jamming radar channels. For example, communications jammers operate on lower frequencies than do radar jammers, the dividing line occurring at about 50 to 100 mc. Also more power per receiver channel is generally required for communications jamming than for radar jamming. On the other hand, the communications channel is very narrow (a few cycles per second for some hand telegraph to a few thousand cycles per second for voice) as compared to the radar channel (fraction of a megacycle per second to a few megacycles per second). Finally, the type of modulation that may be excellent for distracting the communications operator may differ greatly from that which is most effective in obscuring the desired signals on a radar indicator.

It is, in general, more difficult to jam a communications channel than a radar channel. One reason for the greater difficulty is the fact that the desired signal on the communications receiver is usually stronger than the echo signal received by the radar. A second reason is that communications channels, notably radiotelegraph channels, are very narrow.

11.2.3 Airborne, Ship-Borne, Ground-Based, and Expendable Jammers

Jamming by transmitters located on the ground requires a maximum amount of power, whereas expendable jammers require the minimum amount if they are sown, as intended, close to the communications or radar receivers that are to be jammed. This is fortunate, since ground-based equipment has the greatest amount of input power available, whereas expendable jammers have the least. Airborne jammers, on the other hand, are probably the most versatile, since they can reach the most receivers, can generally be carried by the aircraft to be protected, and can be flown over the scene of action. Thus, they can often accomplish the desired result with much less power than even the most advantageously located ground-based unit would require. However, in spite of the advantages of great mobility, relatively low power, etc., airborne equipment is not necessarily the best.

As a practical matter, it may be best to confine airborne equipment to use against particular enemies of the aircraft and to use ground-based or mobile equipment against particular enemies of the ground forces. Individual exceptions to this general policy will, of course, be advisable. An example is the use of ground-based jammers against aircraft-interception [AI] radar and ground-controlled-interception [GCI] communications channels as already mentioned in Chapter 1.

Ship-borne jammers, in general, resemble ground-based jammers more than they do airborne jammers; however, several of the jammers originally intended for airborne use have been adapted to ship-borne installations by the addition of highly directive antenna systems. Considerations similar to the ones given above for airborne versus ground-based jammers apply to the relative value of airborne and ship-borne jammers for naval work.

Expendable jammers, although they offer interesting possibilities, were not used very extensively. Expendable jammers may be of several types, such as parachute-borne (to jam during the period of descent), grounded (to jam from the ground), and floating (to screen

SECRET

naval vessels). In general, jammers of this type will not be effective against systems having highly directive antennas unless the jammers are directly in the beams of the antennas. For this reason and others, expendable jammers for radar have not proved too practical.

11.2.4 Barrage versus Spot Jamming

The process of radiating jamming energy over a band of frequencies so as to be certain of blanketing the victim channel (either communications or radar) is known as barrage jamming. Contrasted to barrage jamming is spot jamming, in which the transmitter is tuned to exactly the same frequency as the victim signal.

A barrage jammer, since it spreads the energy over a large part of the frequency spectrum, requires considerably more power for the same degree of effectiveness than does an accurately tuned spot jammer. Although with a given amount of power spot jamming is more effective than barrage jamming, the former requires the attendance of skilled operating personnel.

In the jamming of radar channels, the type of operation to be undertaken will influence, to a large extent, whether spot or barrage jamming is used. Spot jamming, for example, would probably be used with ground-based jammers operating against one or a few enemy radars. Under such circumstances, however, the need for skilled personnel is no handicap, since such personnel would probably be available anyway to maintain the jamming equipment. In airborne applications, however, the need for an operator and additional equipment may not be compatible with other requirements. Spot jamming is necessary, however, regardless of the extra personnel required and the extra complexity of the equipment involved, if the enemy radar sets are so dispersed in frequency that the amount of power required for barrage jamming is prohibitive. This situation may be the result of careful planning on the part of the enemy (and almost would have to be at the lower radar frequencies) or it may be almost accidental (especially in the microwave region).

In case the enemy elects to place most of his radar in a relatively narrow band, with a few scattered sets outside this band, as was the case in the European Theater of Operations in World War II, a combination of barrage and spot jamming for complete coverage is clearly indicated.

11.2.5 Types of Jamming Modulation

The type of modulation employed for jamming purposes depends upon whether spot or barrage jamming is being employed, upon the vulnerability of the victim receiver to various types of modulation, and upon the kind of modulation that can be produced efficiently at the carrier frequency and power output at which the jammer operates.

In the jamming of communications channels, one consideration in the choice of type of modulation is the psychological reaction of an operator to novel forms of interference. The modulation may be chosen to distract the operator rather than to obliterate the desired signal. This technique is of particular importance when the jammer lacks sufficient power to mask the victim signal completely, since some form of distracting signal, although weaker than the victim signal, may succeed in preventing the reception of any great amount of intelligence. A distracting type of signal does not appear to be effective in radar jamming. Here, the desired display must be obliterated or confused if the jamming is to be effective.

The type of modulation used for spot jammers should be such that the bandwidth of the jammer only exceeds that of the victim channel by an amount sufficient to allow for inaccuracies in aligning the jammer with the victim signal and for the frequency drift of the jammer and the victim channel. Barrage jammers should be provided with a form of modulation that distributes the energy evenly over the band of frequencies that is being barraged. Furthermore, the type of modulation must be such as to avoid "holes" through which the desired signal may be seen. In general, a random type of modu-

lation is more effective than a periodic type since, in many instances, antijamming [AJ] measures may be taken to cope with the latter kind of interference.

Through poor design, some radar receivers may be very vulnerable to some simple form of modulation. Since it is often possible to obtain larger power outputs and relatively simple design when simple types of modulation are employed, such shortcomings of enemy equipment should be exploited. At the same time, the ease with which these weaknesses may be corrected must also be borne in mind, since the useful life of any offensive RCM device depends upon how difficult it is to devise an antidote and put it into service. Antijamming devices for simple types of modulation are discussed in Chapter 13.

Although tests may indicate that a given receiver is particularly vulnerable to a certain type of modulation, it does not necessarily follow in practice that this type is the best to use.

In determining the best type it is necessary to give consideration to the practical aspects of employing this type of modulation in an actual transmitter. For example, one type of modulation may be found to be twice as effective as another; yet it may be possible, with a given amount of input power, to obtain four times as much output with the less desirable modulation. Under these circumstances use of the latter may be indicated.

At the higher frequencies there is a practical limit to the modulation bandwidth that can be obtained. Furthermore, in the case of high-power radar barrage jammers a number of problems are encountered in connection with the modulation of the amount of power that is involved. An understanding of these problems will be of material aid in planning the use of such equipment and in future developments.

Noise modulation, which is now almost universally used for radar jamming, deserves special mention. Noise is a random type of modulation and one in which the energy distribution is uniform, except as it may be influenced by limitations in associated circuit elements. Noise modulation therefore lends itself particularly well to barrage jamming and, for that matter, also to spot jamming. Since it has no periodically recurring frequency, it cannot be filtered out, or eliminated by any other means, without also eliminating the desired signal. As is well known, the noise level is the basic factor that limits the sensitivity of any receiver. Noise generators for use in jamming transmitters are discussed in Chapter 2.

11.2.6 Sideband Energy Distribution

A knowledge of the distribution of energy in the sidebands of a modulated jamming transmitter is essential in planning the details of tactical application of the jammer, especially in barrage jamming. This is particularly true when a number of transmitters must be used to cover the band of frequencies involved. As detailed below, the distribution of sideband energy considerably influences the manner of setting the carrier frequencies of the various transmitters involved in a barrage operation of this type. Information concerning the distribution of the sideband energy is also vital to calculations of the effectiveness of a jammer for protecting a given target against a specific radar.

Theoretically, the distribution of energy in modulation sidebands is confined to specific frequencies when recurrent waveforms are used for the modulation. Consequently, there are likely to be gaps in the spectrum. The widths of these gaps are a function of the parameters involved, and under some circumstances these types of modulation may be entirely unsatisfactory for the purpose in hand.

In practice, the actual distribution of sideband energy may differ considerably from the theoretical values because of the characteristics of the electrical circuits involved. For example, there may be a considerable amount of incidental frequency modulation of the carrier. Under these circumstances, as compared to the theoretical distribution, relatively large amounts of energy are spread over a considerable band in the vicinity of the carrier frequency. A transmitter having incidental frequency modulation is more effective in jamming receivers close to the nominal carrier frequency than if the frequency modulation were not present. The incidental frequency modulation allows

the carrier energy to be effective in jamming, even though AJ devices may be in use.

When amplitude modulation is used, a large amount of the available output energy of a jamming transmitter may be dissipated in the carrier. This suggests the use of some form of carrier-suppressed emission in order that the total output capacity of the transmitter may be available in the modulation sidebands.

A novel form of a carrier-suppressed (really carrierless) emission is employed in the Dina type of transmitter. In its basic form this transmitter consists of a direct-noise amplifier (whence the name Dina), designed to amplify in the r-f range in which transmissions are desired, which is connected to a source of noise. Noise components, at the desired frequency, are thus amplified until they have sufficient power to be radiated. Consequently, there is no carrier and all the available output capacity of the transmitter is made available in sideband energy.

In the design of Dina transmitters, difficulties arise from the necessity of tuning the wideband amplifiers in order to choose the frequency band to be jammed. Greater flexibility and overall simplicity may be achieved by generating the noise energy in a fixed frequency band and heterodyning to the desired transmission frequency. This method has the added advantage that it makes possible the use of the output of the noise source in the frequency range where it is most efficient.

Another important consideration in the design of jammers is the choice of the signal with which the carrier is modulated. If the carrier is modulated with a sine wave, the jamming may actually increase the amplitude of the pip in the enemy radar screen. This effect occurs because the pip "rides on top" of the jamming signal and the increased input to the second detector resulting from the jamming signal allows the second detector to operate on a more favorable portion of its characteristic. If the carrier is amplitude-modulated by noise that is highly clipped (i.e., noise in which the peaks have been cut off) and if the bandwidth of the radar receiver is wide in comparison with the jammer band, the resulting disturbance in the radar scope is flat-topped. The pip rides on top of such a disturbance, and consequently the jamming is ineffectual, even though the frequency coverage may be satisfactory. On the other hand, if the bandwidth of the radar is small in comparison with the jammer bandwidth, the resulting disturbance on the radar scope is sufficiently irregular to mask the pip effectively. This problem does not arise when the carrier is frequency-modulated by noise.

11.2.7 Jamming Power Requirements

In general, it is desirable to employ as much jamming power as possible. As a practical matter, however, the weight, bulk, portability, and power drain of the equipment often determine the size of the transmitter that can be used. Furthermore, it is not economical on any score to provide jamming transmitters that are appreciably larger than necessary to accomplish the desired end.

The exact calculation of the jamming power required in order to effectively neutralize a given radar system involves a knowledge of such factors as the power output of the enemy transmitter, the transmitting and receiving antenna gains and directivity patterns (in both the vertical and the horizontal planes), the distance between the jammer and the receiver, the strength of the desired (from the enemy viewpoint) signal at the receiver, the jam-to-signal [J/S] ratio for the type of modulation involved, and the effective size of the target. The exact mathematical relationships whereby the jamming power, for a specific case, may be calculated are discussed in Chapter 6. The manner in which the various factors involved influence the jamming power requirements will be outlined here. A knowledge of these relationships is of considerable value, since, if the performance of a given jammer against a given enemy system is known, an accurate estimate can be made of its performance under slightly different conditions.

In radar jamming, the closer the target is to the radar, the greater is the power required for jamming. This is so since the strength of the receiver echo increases as the distance between the target and the radar decreases, and

more jamming power is therefore required to obliterate it. This condition exists even when self-screening is practiced (target carries a jammer) because, although the jamming signal received at the radar thus increases as the target approaches, the size of the echo increases at a greater rate. For this reason, the *minimum* distance at which a jammer can screen a given target is a measure of the effectiveness of the jammer. In general, however, it is to be noted that considerably less power *per channel* is required for radar jamming than for communications jamming. This is true largely because of the fact that in the former it is necessary to obliterate only an echo, whereas in the latter it is necessary to cope with a direct signal.

If the distance at which a jammer is effective is determined by experience for a given set of circumstances, the performance to be expected under other conditions may be estimated from the following relationships. Other factors being equal, the minimum distance at which a given radar jammer will be effective is:

1. Directly proportional to the square root of
   a. the effective echo area of the target;
   b. the effective peak power of the radar;
   c. the power gain of the radar transmitting antenna;
   d. the jam-to-signal power ratio for the type of modulation employed.
2. Inversely proportional to the square root of
   a. the jammer output power;
   b. the power gain of the jammer antenna in the direction of the radar.

11.2.8 Jammer Frequency Setting

If the jammers are otherwise in good operating condition, the success of any plan of jammer activity depends entirely upon the accuracy with which the transmitters are adjusted to the victim frequency. In the manually adjusted transmitters used for spot jamming, therefore, means must be provided for determining the victim frequency and for accurately adjusting the jammer to this frequency.

In spot jamming, the jammer carrier must be set as closely as possible to the frequency of the victim signal. In ground-based or ship-borne equipment this does not present a serious problem since ample equipment and operating personnel can generally be made available. In airborne installations, on the other hand, the need for conserving weight and personnel makes it desirable to preset the jammer to the proper frequency on the ground before take-off. Unfortunately this cannot be done to spot jammers because of the setting accuracy that is required. Deviations introduced by receiver or frequency meter calibration inaccuracies, by reading and resetting errors, and by frequency drifts in both the frequency meter and the transmitter due to changes in temperature, pressure, humidity, and power-supply voltages, all combine to make it impractical to preset spot jammers. The accuracy required is at least 0.5 mc or so in radar jamming. Overall accuracies of 0.1 per cent or considerably better are evidently necessary.

Even though it may not be feasible to preset an airborne spot jammer prior to take-off, the equipment should be adjusted before take-off as closely as possible to the frequency to be jammed. To make a major frequency change in the air is generally difficult and time-consuming. Furthermore, by setting the equipment as closely as possible to the desired frequency, the performance of the set can be accurately checked at approximately the frequency at which it will be used.

As contrasted to spot jammers, barrage jammers can usually be preset to the proper frequency band and, in airborne equipment, the attention required during flight can thus be reduced to simply turning the equipment on and off at the proper time.

The bandwidth of a radar barrage jammer is seldom great enough to cover the entire band over which the enemy radar is likely to be spread. Furthermore, because of the limited output power of all but the most recent types of available airborne barrage jammers, one or more units are generally required in each aircraft that is to be screened. When only one or two transmitters are involved in a given operation, they should be accurately adjusted so as to span the spectrum in which the enemy radar carriers are most likely to be located.

In large formations, however, where many

jammers are available, it is important that their frequencies be *accurately* adjusted so that the maximum possible number of channels are occupied by the jammer *carriers*. This may be done by carefully spacing the carriers uniformly across the band occupied by the enemy systems. Under these circumstances the carriers, particularly if they have incidental frequency modulation, contribute greatly to the jamming effectiveness. In an operation of this kind, the absolute accuracy of the frequency meter used for setting the carrier frequencies need not be very great since it is only the relative accuracy that is important, particularly if it is possible to check all transmitters against the same frequency meter.

Automatically Tuned Jamming Equipments

It is sometimes practical to use automatic devices that seek the victim signal, accurately align the jammer to its frequency, and then periodically monitor the enemy transmissions in order to terminate the jamming as soon as the enemy no longer uses the channel that is being jammed. Because of the feature of listening through one's own jamming, these devices are sometimes called "listening-through" systems.

A considerable number of laboratory designs for such equipment were perfected, and serious consideration was given to the widespread operational use of such devices, but no large-scale procurement was made, because of the rapidly changing tactical situation and other considerations. It must be remembered, for example, that some provision must be made to prevent several automatic jammers in airborne applications from locking on one another. This difficulty does not arise in night operations or in isolated daytime flights, when the aircraft are likely to be separated from one another by considerable distances.

The type of automatic operation that is used will depend upon the enemy system. For example, if the theater of operations is one wherein the enemy radars are so widely spaced that only one need be jammed at a time, the automatic operation may be one in which the jammer seeks the enemy frequency, transmits jamming signals thereon, and periodically listens through to see if the victim signal is still there. When it is no longer present, the jammer ceases to operate and then searches for the next signal to be jammed, repeating the whole process over and over again. This type of operation has one possible hazard. If the enemy should have available fighters that are equipped to home on the jammer-carrying aircraft, there is the possibility that the latter may be intercepted.

Another type of operation would be one in an area in which there are many radars, a number of which may follow a given target at the same time. In this case, the automatic jammer operation may be one wherein the jammer seeks an enemy frequency, jams the first one encountered for a predetermined length of time (say from 30 sec to 2 min), then stops and seeks the next (as regards frequency) signal, jams it, and then moves on, etc. This type of operation can be effective against GCI and gun laying [GL], even though all radars are not jammed all the time, since in either case accurate data are required for some period of time in order to make an interception or to provide accurate data for gunfire. The type of jammer operation just described is also effective in preventing homing on the jammer by interception, since the length of time the jamming emission stays on any one frequency is relatively short. This type of operation is especially effective when used by a large formation of aircraft. In this case, the jammers will considerably outnumber the radars, so that the probability of a given radar remaining unjammed for an appreciable time is very small indeed. Radars will be unable to obtain direction-finding [DF] cuts on the jammers because of the constantly changing direction from which the jamming comes and because of the fact that they are generally receiving signals from two or more jammers simultaneously.

It should be borne in mind that there is a simple counter-countermeasure for any listening-through device that stops jamming and moves on to the next signal as soon as the victim signal disappears. The victim station would only have to interrupt his transmissions long enough for the jammer to note its absence

and to cease jamming. It would then be possible to make use of the equipment that had been jammed, at least until the jammer again returned to its frequency. From the point of view of the jammers, difficulty on this score can be obviated by jamming any signal for a predetermined period of time without listening through.

The Systems Approach

Whenever it is necessary to employ spot jamming, the question of exactly what combination of transmitting, receiving, and indicating to use arises. The answer varies widely with the particular application. The first widely used spot-jamming setup consisted merely of a standard search receiver and three standard jamming transmitters. The operator simply listened to a signal, tuned a jammer to the signal, and then searched for another signal to jam, returning periodically to the original signal to monitor the effect of the jamming. With various portions of the spectrum assigned to different operators, a very creditable job was done with this comparatively simple equipment.

A much more ambitious program than that described above may be necessary. This was first realized in connection with the design of ship-borne equipment, since in this case it is necessary to screen a very large target with moderate amounts of power. This frequently predicated the use of directional-jamming antennas, with the accompanying difficulty of locating the direction as well as the frequency of the enemy radar. These factors, together with the problems sometimes encountered of distinguishing between enemy and friendly radars at or near the same frequency and carefully coordinating the activities of each jamming transmitter with other jamming transmitters on the same or other vessels and with other electronic gear which might be in use, made it desirable to develop a rather elaborate jamming system. Such a system consists of various receiving equipments with associated indicating devices (such as pulse analyzers and panoramic-presentation units), direction-finding equipments, jamming transmitters, antennas, suitable communications with various other points, etc. Examples of such systems will be discussed later.

Besides the advantages listed above, such systems generally possess the additional important feature that each component is specifically designed to function efficiently in the presence of the rest of the system. This is especially important in airborne work, since the various components must frequently work in close proximity to one another. It is also frequently possible to devise an integrated system which will eliminate some of the "extra" features of combinations of standard items (e.g., some of the features of search receivers designed purely for investigational work) with a corresponding saving in complexity and weight. These considerations, rather than the usual complexity of the job to be done, dictate the use of systems for airborne applications.

Tactical Considerations

Radar jamming transmitters should, as a rule, be used only as much as is necessary to accomplish the desired results. This practice will hinder DF and homing on the jammers by the enemy and, incidentally, will limit the time during which the enemy operators can study and become accustomed to the particular type of the jamming signal being used. As mentioned elsewhere, one of the most effective AJ measures is sufficient operator training and experience. Conversely, the element of surprise plays a large part in determining the effectiveness of a jamming operation.

In radar jamming there is still another reason for limiting the use of the jammers as much as possible. When self-screening is used (that is, where the target to be screened from the enemy radar is carrying its own jammer), if the jammer is turned on before the craft is within the field of view of the radar, its presence will be revealed to the radar. This results from the fact that the strength of the emissions from the jammer considerably exceeds the strength of the radar echo (except when the target is close to the radar) and, consequently, the radar receiver will respond to the jamming transmissions long before it receives a sufficiently strong echo to detect the presence of a target. Although neither the size

of the target nor its range can be ascertained by reception of jamming emissions, its bearing will be revealed and a warning given of the possibility of an attack from that quarter.

An exception to the general philosophy of limiting jamming transmissions as much as possible would be in an instance in which a false appearance of activity is to be created. Just as in communications deception practices, if the enemy comes to associate jamming operations with increased activity, it may be desirable, on occasion, deliberately to operate jammers for deception and confusion purposes.

Although the size and shape of a formation will undoubtedly be dictated by tactical considerations, it should be borne in mind that these factors also influence the jamming effectiveness. The effectiveness of airborne radar jamming transmitters used for self-screening can be increased considerably if the formation of planes is made up so that the aircraft are all within the beamwidth but are not all within the distance corresponding to the radar pulse length. The jammers on all the planes will then contribute to the jamming effectiveness but only those planes which are within the distance corresponding to the pulse length will contribute to the amplitude of the echo. The echoes from the various aircraft will be spread on the radar screen and, therefore, the amplitude of the jamming signal needed to cover them up need not be so great as it would be if all echoes added together in height.

11.3 TYPICAL TRANSMITTING EQUIPMENT

Radar jamming transmitters fall into a relatively few fairly closely related categories according to intended use and power output levels. These categories, together with the characteristics of the various transmitters in each category, are shown in Table 1. The following comments are intended to amplify and explain Table 1.

11.3.1 Low- and Medium-Power Conventional Tube Transmitters

The accompanying monograph[809] covers the technique developments used in the building of these transmitters in considerable detail. Most of the equipments listed consist merely of a tunable transmission line type oscillator (open-wire type line for conventional triodes, double-coaxial type line for lighthouse tubes) which is amplitude-modulated by a standard noise source and amplifier (see Chapter 2).

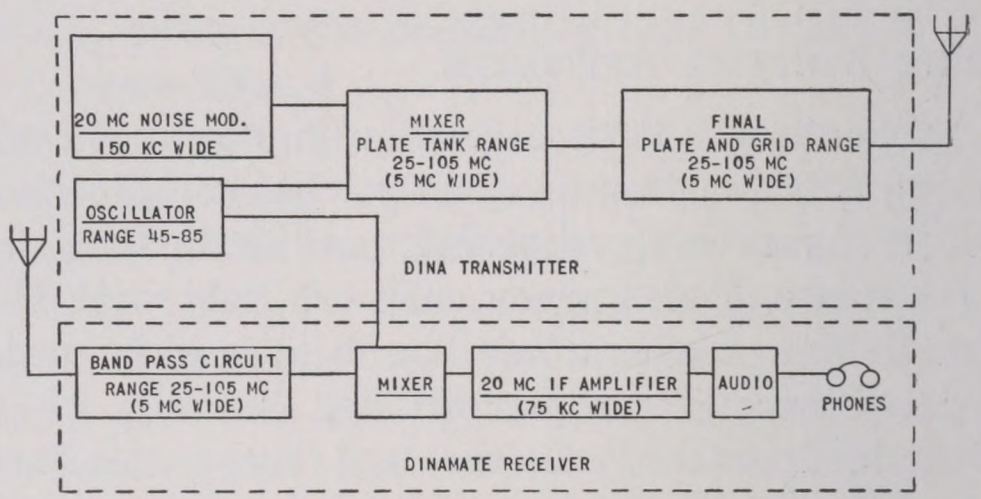


FIGURE 1. Block diagram of Dina-Dinamate receiving and jamming equipment.

The direct-noise amplifier type of jamming transmitter deserves special consideration, since the design of the transmitter itself is somewhat unusual and also since a "setting-on" receiver forms an optional component of the overall jammer. One of these equipments (AN/ARQ-8) will be described in some detail: the equipment (see Figure 1) consists of a suppressed-carrier transmitter (achieving the same result as the direct-noise amplifier) and a superheterodyne receiver operating over the same range as the transmitter. A control box is provided to allow operation from a remote position. In the example chosen, both the transmitter and receiver operate over the range 25 to 105 mc, with a power output of 20 w for the transmitter. The receiver r-f input and transmitter tank circuits have a bandwidth of 5 mc so that satisfactory operation may be obtained over this incremental range by tuning only the oscillator, which is common to both units.

The transmitter consists of a 150-kc wide noise source (which may be replaced by a 4 mc wide noise source for barrage jamming) centered at 20 mc and a 45- to 85-mc heterodyning oscillator, plus a mixer stage and power amplifier. The r-f tank circuits, the mixer, and power amplifier are broad-band, as mentioned above, and tune over the range 25 to 105 mc, so that tuning only the oscillator places the 150-kc wide

TABLE 1. Radar jamming transmitter developments.

Identification Nos.	Use	Tuning range (mc)	Power output (watts)	References	Comments
	Low- and medium-power conventional tube transmitters				
RRL: B-1700 Div. 15: RP-162 Navy: CXCE	Ship-borne practice jammer	85-115	15	511	
RRL: B-2000 Div. 15: RP-163 Army/Navy: AN/SPT-3	Airborne or ship-borne	85-135	10	365, 531	Modification kit available to convert frequency range to 125 to 150.
RRL: B-4500 Div. 15: RP-163	Airborne	70-250	20		Revision of above transmitter, employing same principal components, etc.
RRL: B-2200 Div. 15: RP-309 Army/Navy: AN/APT-1 AN/SPT-1	Airborne or ship-borne	90-220	12	409, 462	Direct-noise amplifier. Modification available (but never produced in quantity) incorporating "setting-on" receiver.
RRL: B-2800 Div. 15: RP-218 Army/Navy: AM-14/APT	Power amplifier	85-150	140	362	Amplifier for above transmitters.
RRL: B-3400 Div. 15: RP-329 Army/Navy: AM-18/APT	R-f amplifier	140-210	50	396	Amplifier for above transmitters.
RRL: B-2900 B-3200 Div. 15: RP-250 RP-207 Army/Navy: AN/ARQ-8	Airborne or ship-borne	25-100	30	367, 421, 557	Direct-noise amplifier. Includes "setting-on" receiver.
RRL: B-4100 Div. 15: RP-344 Army/Navy: AM-33/ART	R-f amplifier	26-105	150	110	Primarily intended for use with above transmitter.
RRL: F-1500 Div. 15: RP-164 Army/Navy: AN/APQ-2 AN/SPT-4	Airborne or ship-borne	200-550	15	704	Modification available to extend frequency range down to 150 mc.
RRL: F-902 Div. 15: RP-165 Army/Navy: AN/APT-2 AN/SPT-2	Airborne or ship-borne	450-720	5	360, 440, 541, 619, 652	
RRL: F-4300 Div. 15: RP-165 Army/Navy: AN/APT-2A					Revision of above transmitter to provide single-dial tuning and other improvements.
RRL: F-2500 Div. 15: RP-166 Army/Navy: AN/APQ-9 AN/SPT-5	Airborne or ship-borne	475-585	20	360, 447, 558	

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TABLE 1. (*Continued*)

Identification Nos.	Use	Tuning range (mc)	Power output (watts)	References	Comments
RRL: F-3500 Div. 15: RP-336 Army/Navy: AN/APT-5	Airborne	350-1,200	15	472, 645, 694	Can be tuned to 1,400 mc. Modification can be made to allow tuning down to 200 mc.
RRL: F-3505 Div. 15: RP-275 Navy: AN/SPT-6	Ship-borne	350-1,200	15	472, 645, 683	Ship-borne modification of above transmitter.
RRL: F-4800 Div. 15: RP-428 Army/Navy: AN/APT-9	Airborne	300-2,500	15		Can be modified to tune down to 200 mc. Part of AN/APQ-21 jamming system described below.
		Medium- and high-power transmitters			
RRL: F-3300 Div. 15: RP-285 Navy: TDY/CXFR	Ship-borne	350-800	150		Later modifications made by manufacturer extended frequency range above and below that given.
RRL: F-3400 Div. 15: RP-338 Army/Navy: AN/APT-4	Airborne	150-400 350-780	150	466, 606, 642	Uses separate tubes for separate ranges. Another modification developed (AN/APT-7), but not produced, extending frequency range down to 90 mc.
RRL: F-4400 Div. 15: RP-338 Army/Navy: AN/APT-8	Airborne	750-1,200	100		Airborne magnetron transmitter developed but never produced.
RRL: A-500 Div. 15: RP-100 Army/Navy: AN/MPQ-1	Ground-based against AI	480-500	50,000	353, 587, 720	Several units built for use in England.
		Automatic jammers and jamming systems			
RRL: F-1800 Div. 15: RP-167 Army/Navy: AN/APQ-1	Automatic jamming transmitter	475-585	5	358	Sweeps any 40-mc band within frequency range.
RRL: U-600 Div. 15: RP-380 Army/Navy: AN/APA-27	Automat automatic jammer control	Depends upon jamming transmitter used		481	Control unit for use with standard search receiver and many standard jamming transmitters.
RRL: S-1200 Div. 15: RP-458	GL airborne jamming system	Band around 200 mc	15		Employs AN/APQ-2 transmitter listed above plus standard search items in long-shaped case. Provided with slot antennas.
RRL: F-4500 Div. 15: RP-414 Army/Navy: AN/APQ-20 (XA-1)	Airborne jamming system	2,300-4,200	10		Includes klystron transmitter plus standard receiver, panoramic adapter, antennas, filters, etc. Ship-borne modification also designed. No large procurement because unit was superseded by following items.

TABLE 1. (*Continued*)

Identification Nos.	Use	Tuning range (mc)	Power output (watts)	References	Comments
RRL: F-5100 Div. 15: RP-424 Army/Navy: AN/APQ-20(XA-2)	Airborne jamming system	2,230-4,030	50	688	Complete system includes magnetron transmitter plus standard receiver, panoramic adapter, filters, antennas, etc.
RRL: F-5150 Div. 15: RP-424 Army/Navy: AN/APQ-27	Airborne jamming system	2,230-4,030	50		Same as above, except includes remote tuning and other improvements.
RRL: F-4800 S-1400 Div. 15: RP-428 Army/Navy: AN/APQ-21	Airborne jamming system	1,000-2,500	15		Includes AN/APT-9 transmitter described above plus standard receiver, panoramic adapter, etc.
RRL: F-9000 Div. 15: RP-457 Navy: XMBT	Ship-borne jamming system	2,000-4,000 90-260	1,000	See text	See text for complete description.
Army/Navy: AN/TPT-1	In ground-based jamming system	90-220	100 or 50		Consists of AN/APT-1 plus associated amplifiers and directive antennas for ground-based operation.

noise band anywhere in a preselected 5-mc portion of the 25- to 105-mc range. The lower sideband developed by heterodyning the 45- to 85-mc oscillator with the 20-mc noise source becomes the output frequencies 25 to 65 mc and the upper sideband similarly becomes the output frequencies 65 to 105 mc. The transmitter may be used quite independently of the receiver, especially when provided with the wide-band modulator mentioned above for barrage jamming.

The receiver is designed to work in conjunction with the transmitter by using the oscillator in the transmitter as its local oscillator. Since the transmitter operates at a frequency that is 20 mc higher or lower than its oscillator frequency, the use of a 20-mc i-f amplifier in the receiver permits setting the transmitter on the desired frequency by merely tuning in the receiver on the signal to be jammed.

The circuit matching the antenna to the mixer of the receiver is 5 mc wide. The antenna tuning is preset to the 5-mc frequency range desired and any station in that range may be tuned in by varying only the transmitter oscillator. Thus, the complete system is tunable over the 5-mc incremental band by means of a single control.

As shown in the chart, a higher-frequency version of this equipment (AN/APT-1) is also available. There are also r-f amplifiers available for use with the transmitter to increase the power output to well over 100 w over most of the frequency range.

11.3.2 Medium-Power Magnetron and High-Power Transmitters

The medium-power magnetron transmitters listed in Table 1 need very little comment except that given under the discussion of techniques in the accompanying monograph.[809] Reports have been issued describing the general features[466] of, and the results obtainable[606, 642] with, these transmitters.

The very high-power ground-based jamming transmitter listed requires some special comment. This transmitter employs the resnatron tube (described elsewhere[809]) and is a complete jamming unit consisting of seven trucks, including power supplies, highly directive anten-

nas, etc. The unit was designed for use against the German night fighters equipped with AI radar. It was intended to provide a lane of safety[587] for bombers along a selected route. The construction and operation of the unit, which was extremely complex, is described elsewhere.[657, 720]

11.3.3 Automatic Jamming Transmitters and Jamming Systems

As indicated in Table 1, several automatic jamming transmitters and several jamming

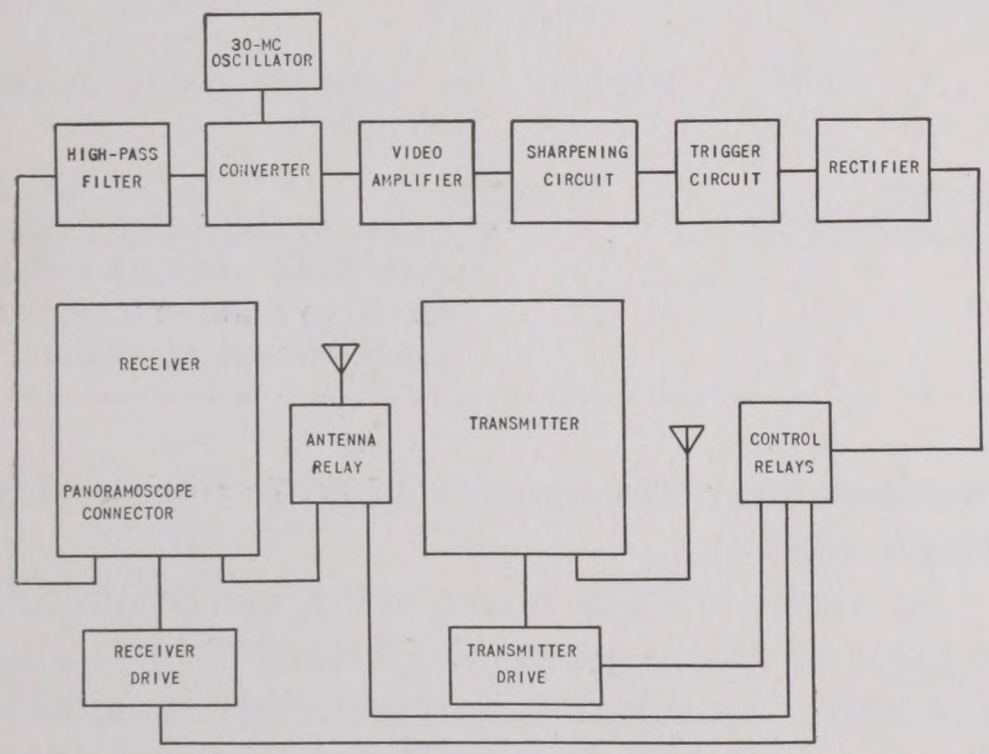


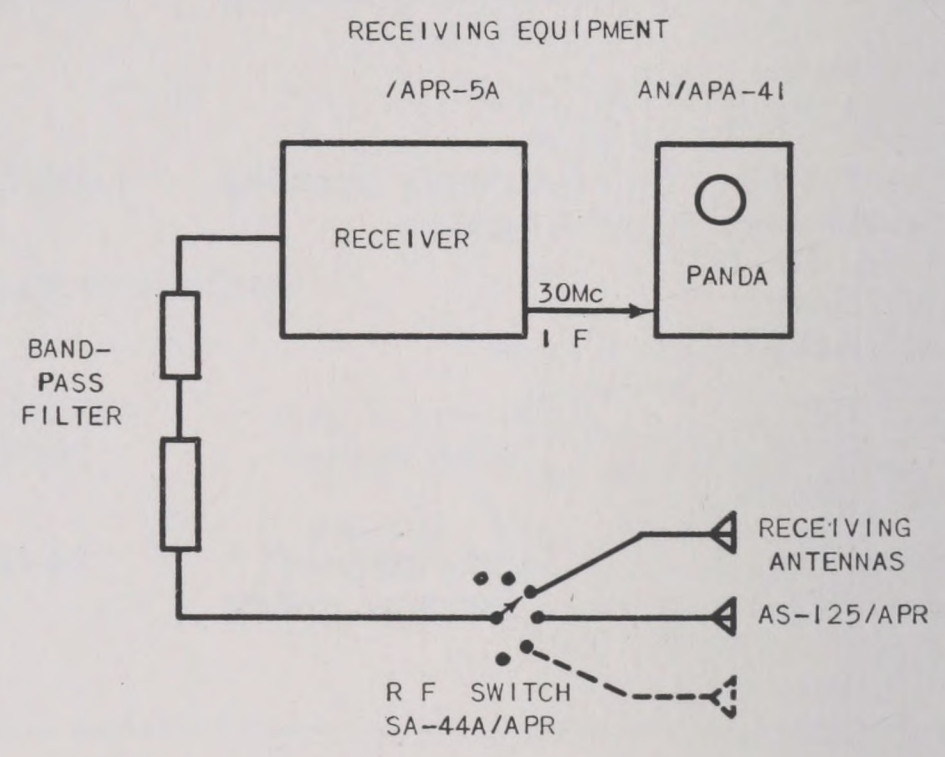
FIGURE 2. Block diagram of Automat automatic jammer setting-on equipment.

systems have been developed. One of these automatic jammers and two of the jamming systems will be described as examples of the type of design employed.

AUTOMATIC JAMMING TRANSMITTERS

Several attempts to design a satisfactory automatic jamming system, especially for the purpose of eliminating the necessity of carrying operators on spot-jamming missions in the European Theater of Operations, were made but, although two equipments were developed, no large-scale production was ever completed. One of these equipments was actually a modification of the AN/APT-2 transmitter, providing an autodyne receiver for use with the transmitter but using the same oscillator circuits, modulator circuits, etc., as the original transmitter. This model[816] was carried to the stage of preproduction engineering by a manufacturer, but changes in tactical situations made it unnecessary to go through with extensive production plans.

A parallel development[22] was carried out to accomplish the same results in a somewhat more general manner. This development (Pimpernel) made use of a separate receiver and drive unit which first tuned in the signal and then tuned an AN/APT-2 or other similar transmitter to the signal frequency.



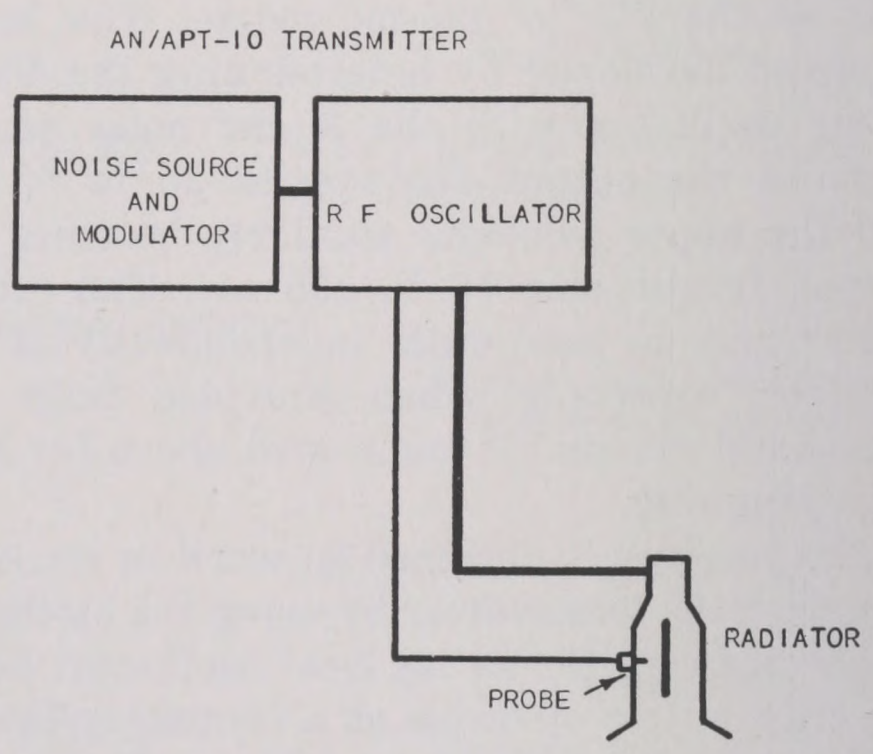


FIGURE 3. Block diagram of AN/APQ-20 S-band airborne jamming system.

With these fairly early approaches as a basis, an attempt was made to develop a generally useful automatic jamming attachment. This system (Automat) consisted of a device which was

to be used in conjunction with a standard search receiver and a standard jamming transmitter to convert the combination into an automatic jamming system. Small motor-drive units are supplied to attach to the front panels of the receiver and transmitter for automatically sweeping them over a selected frequency range. Separate antennas for receiver and transmitter are required. The receiver antenna is used by

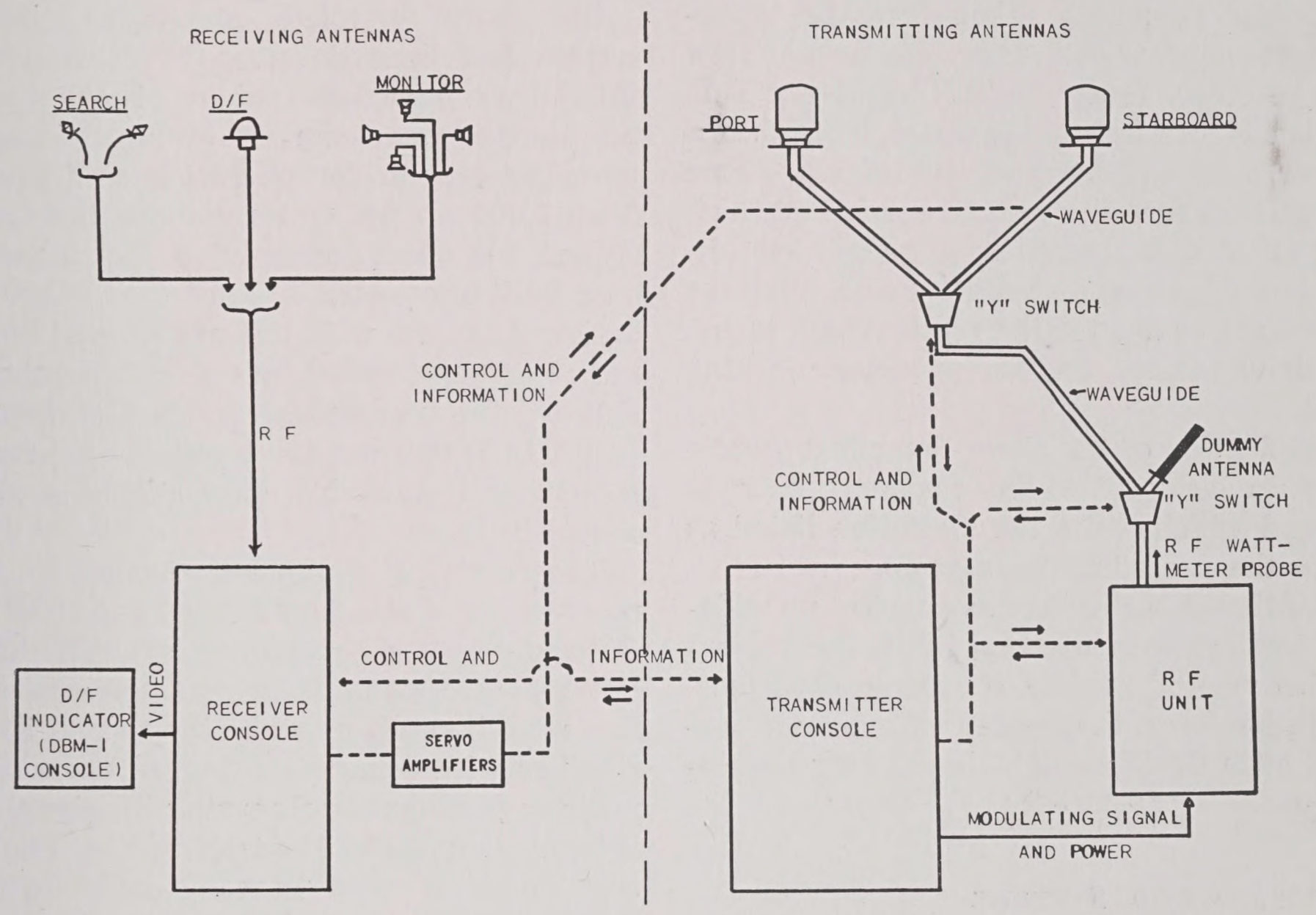


FIGURE 4. Block diagram of Elephant ship-borne jamming system.

the receiver to pick up the jammer. Since there are no mechanical connections between units, they may be mounted in any relation to one another. A block diagram of this jamming system is shown in Figure 2.

This equipment may be operated in three separate ways. In the first place, completely manual operation may be employed; that is, the receiver may be tuned to a signal by hand and the transmitter tuned by hand to the receiver frequency. A modification of this first method is to use the transmitter as a barrage jammer and the receiver as an ordinary search receiver. The second method of operation involves manually tuning the receiver to the signal which it is desired to jam and then allowing the system to lock the jamming transmitter on frequency. The third method of operation is completely automatic. The receiver automatically sweeps the selected frequency band and stops on the first signal received. The transmitter then starts sweeping, locks on the receiver frequency, and jams for ½ to 7 min, depending on the settings of the time-delay circuit. At the end of the jamming period, all relays are restored to starting positions. At this point, several different methods of operation are possible, depending on the selected position of switches inside the unit. Any combination of the following re-

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ceiver and transmitter functions may be used.

1. Receiver relocks on same signal without moving (if signal is still there).
2. Transmitter relocks on receiver without sweeping.
3. Transmitter leaves receiver frequency and resweeps before locking on.
4. Receiver leaves signal and locks on next signal encountered.

The Automat circuits are operated from the intermediate frequency taken from the panoramascope output connector on a standard search receiver (such as AN/APR-4). This signal is fed through a high-pass filter into a converter tube and heterodyned with a 30-mc oscillator, thus forming video frequencies which are amplified and applied to a trigger circuit, the output of which is rectified and operates the necessary relays for the receiver and transmitter drive motors, and the automatic locking clutches.

A modification of the above-described system has been developed which responds only to pulses and which omits the operation listed as No. 4 in the preceding paragraph.

As mentioned earlier in this chapter, no widespread tactical uses of these units have been made, because of rapidly changing situations. It is felt, however, that under different circumstances, such devices might be of very considerable use.

Airborne Jamming Systems

As shown in Table 1, several airborne jamming systems have been developed. One of these is described in detail, as an example of the type of design employed. These systems are generally quite similar except for frequency range covered and minor details of construction, and further details may be obtained from the references cited.

A block diagram of the AN/APQ-20 (XA-2) jamming system is shown in Figure 3. This system is a complete, manually tuned spot-jamming equipment consisting of receiving equipment and a jamming transmitter. The receiving equipment includes a panoramic-presentation unit for use in setting the jammer on the received signal. The essential components of the system are an AN/APR-5 receiver and an AN/APA-41 panoramic adapter (see Chapter 10), an APT-10 (XA-2) transmitter, and several antennas (see Chapter 4). A band-pass filter to prevent reception of spurious signals is also provided.

Ship-Borne Jamming Systems

One very complete ship-borne jamming system has been developed.[817] This complete ship-borne jamming system (Elephant) was the result of an attempt to develop an integrated jamming system for operation at frequencies from 1,000 mc up. One complete experimental system for operation only in the S band has been built and tested on sea trials. Other units, designed for use with this system and built but not completely tested, are a low-frequency r-f unit for the transmitter and a high-frequency (6,500 to 11,000 mc) tuner unit for the receiver. A schematic-assembly view of the system is shown in Figure 4.

The receiving equipment consists of a dual receiver and a standard Navy Type DBM radar DF equipment (see Chapter 10). The dual receiver provides one receiving channel to operate as a search receiver, while the second identical receiver with separate antennas operates as a monitor receiver for observing the signal which is being jammed by the transmitter. The direction finder is used in conjunction with the search receiver to obtain a bearing on the signal to be jammed and as an aid in the identification of signals. The receivers provide single-signal reception over a tuning range of 2,000 to 4,000 mc, present the signal on an oscilloscope, and indicate on meters the pulse width and prf of the signal.

The transmitter is a 1-kw noise-modulated transmitter composed of a main transmitter console housing the modulator, power supplies, control equipment, and the Mark III r-f unit which consists of the tunable magnetron oscillator. This magnetron is tunable between 2,460 mc and 3,610 mc. The r-f output of the transmitter is fed to the transmitter antenna system through a wave guide. Two rotatable direc-

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tional antennas are connected through a Y switch so that selection of the one providing unobstructed radiation may be made. These narrow-beam antennas permit full 360-degree coverage in azimuth. The vertical beamwidth is sufficient to allow for roll of the ship. Radiation is circularly polarized. Another waveguide switch permits the transfer of the transmitter output to a dummy antenna during standby or tuning operations.

11.3.4 Expendable Transmitters

No development work was undertaken by Division 15 on expendable transmitters for radar jamming. A theoretical study of one such device was made with the conclusion[555] that such equipment might be useful under rather specialized circumstances but was not of enough general interest to warrant an expensive developmental program.

Chapter 12

RADAR DECEPTION AND CONFUSION

12.1 INTRODUCTION

VARIOUS IMITATIVE methods designed to create confusion or deception of enemy radar operation have been developed. For convenience, these devices may be classified into mechanical and electrical means. In addition, just as in the communications field, manipulative countermeasures deception may also be practiced.

Under the category of mechanical confusion there are various reflector devices which act as decoy targets. They serve to confuse (and sometimes deceive) the radar operator by creating false signals which closely resemble those from a legitimate target. These reflecting surfaces are generally known as Window. The use of such material for creating confusion is known as a Window operation.

Electrical deception may be carried out by means of specially developed devices or by using the jammers previously described in this publication. To do this, a small diversionary force carries enough jammers to make it indistinguishable from the genuine attacking force carrying jammers for its own protection. This will be elaborated upon later.

Manipulative radar countermeasures deception, as the name implies, is the use of countermeasures devices to mislead the enemy as to our intentions by creating such activity at times other than when an actual offensive operation is under way. The importance of countermeasures at times other than during an actual operation cannot be too strongly emphasized. Prisoner-of-war reports indicated that, in certain theaters, advance notice of impending operations was always given to the enemy by the appearance of intensive countermeasures activity.

Radar manipulative deception requires careful attention to details. Search receivers can readily determine the enemy radar equipment that is in operation and countermeasures activity may then be directed against it in order to attract attention. Furthermore, it may be possible to determine the success of such activity by observing whether the enemy radar ceases operation, shifts to another frequency, or otherwise changes its normal plan of operation.

Most of the work on deception and confusion methods was done by the Radio Research Laboratory under contract OEMsr-411. Important contributions were made, especially to the work on corner reflectors (Kites or Angels) and to the work on electrical deception devices, by the General Electric Company under contract OEMsr-931.

12.2 GENERAL DESCRIPTION OF WINDOW

The various types of Window can be divided simply into two classes, tuned and untuned. The tuned varieties respond most effectively over fairly narrow frequency bands of the order of plus and minus 7 to 10 per cent, while the untuned varieties respond to much wider frequency bands. No practical form of Window, however, acts independently of frequency, and all that have been used show a maximum efficiency at some frequency.

12.2.1 Types of Window

Tuned Window consists normally of dipoles that give a maximum power response when cut to half wavelength (0.475 wavelength for straight dipoles). The response is still appreciable near multiples of the fundamental frequency, decreasing somewhat more slowly than the inverse square of the frequency ratio. When several graded lengths of dipoles are packaged together, the practical distinction between tuned and untuned Window is obscure, although the distinction remains clear from the viewpoint of theory and design.

The following types of Window have proved to be of varying practical value.

1. Tuned reflectors (dipoles).
   a. Chaff,[a] narrow strips of embossed or

[a] Manufactured and used in quantity.

SECRET

paper-backed aluminum foil, bent longitudinally into a flattened-V cross section by means of Chaff cutters.

b. Flat Chaff[b] (British Window), cut by guillotine from paper-backed aluminum foil.

c. Tuned Rope, consisting of dipoles in longitudinal sequence, physically supported by means of a nonconducting medium.

d. Wires.

e. Turnstiles, each made from three dipoles held mutually perpendicular at their centers.

2. Untuned reflectors.

a. Rope,[b] 400-ft streamers of narrow (½-in.) foil, packaged three rolls per bundle.

b. Corner reflectors (Angels or Kites), constructed from three mutually perpendicular planes of conducting material, and diplanes, constructed from two mutually perpendicular planes of conducting material.

c. Squares or sheets.

The following sections present a more detailed description of the design and manufacture of the above types of reflectors and a brief discussion of the properties of each. A tabulation of manufactured types of Window is included in Table 1.

12.2.2

Chaff

The elementary theory of Chaff[499, 590, 602] shows that the radar echo of a half-wave dipole is only slightly dependent upon the cross section of the dipole. The width of the frequency band of the Chaff response varies rather slowly with the width of a thin strip, approximately as the one-third power. As a consequence of these facts, a given radar echo can be obtained with a minimum weight and volume of Chaff if the dipoles are made as thin and as narrow as possible. A simple calculation will show that, if it is desirable to cover a wide frequency band, the use of two or more lengths of very narrow strips will result in lighter weight and less volume than the use of wide strips. Because weight and volume are prime considerations when Window is to be carried in aircraft, every effort has been made to reduce the width and thickness of the strips to a minimum value.

The most suitable material for Chaff is aluminum foil. It is a lightweight conductor which can be produced in quantity and rolled easily to extreme thinness. The thickness of the foil and the width of the strip cannot, however, be reduced indefinitely in order to reduce the weight and volume of the Chaff. A practical consideration must be met, viz., the individual strips in a package must separate when the package is opened in the air. The consequence of too light a foil or too narrow a strip is that the dipoles coalesce into a mass when released in the air and have no opportunity to function individually in producing a radar response. The phenomenon is known as "birdnesting" and has been a controlling factor in fixing the lower limit of thickness and width of Chaff dipoles.

As a means of obtaining greater rigidity in narrow strips of thin foil, a machine was designed to cut the strips from a continuous sheet and to give the individual strip a longitudinal bend resulting in a flattened-V cross section. This method of manufacture has been adaptable to mass production in great quantities and produced an exceedingly light type of Chaff. The so-called Chaff cutting machines (Figures 1 and 2) operate on the principle of the lawn mower in that a rotary set of blades cuts against a fixed blade. A sheet of foil is fed continuously into the cutter, the width of the sheet having been pre-slit to the desired length of the dipoles. The longitudinal fold of each dipole is produced by alternate blades of the rotary cutter which have been ground back in order to bend rather than to cut the foil. Hence, as the sheet is fed continuously into the cutter, each dull blade produces a fold and each sharp blade cuts off the bent strip. Present machines cut 10 strips per revolution and about 8,000 per minute. As many as four layers of foil are often cut simultaneously, thus greatly increasing the production rate, but, when more than one layer is cut at a time, the speed of the machine is somewhat reduced.

[b] Manufactured and used in quantity.

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The practical limit of foil thickness has proved to be slightly less than 0.001 in. Large quantities of thickness 0.0008 in. and also of 0.0009 in. have been manufactured. Widths of approximately 10 in., as in the Army Chaff RR-4/U (Figure 3) used against the German Wurzburg, the birdnesting amounts to 10 to 25 per cent. The frequency band from the resonant

TABLE 1. Types of Chaff and Rope.

Type		Band		Units	Gross	Number				
Army/ Navy	Army	covered (mc)	Polarization	per bundle	bundle wt (lb)	of pieces	Lengths*	Width (in.)	Foil (in.)	Remarks
RR-2/U	CHR-1	–350	Vertical	....	0.8	3	400′	0.50	0.0009 hard	Each of 3 rolls in inner sleeve $\frac{5}{8}\times3\frac{1}{16}\times3\frac{1}{2}''$, parachute, and 15-ft. cloth leader.
RR-3/U	CHR-2	–350	Both	....	0.8	3	400′	0.50	0.0009 hard	Each of 3 rolls in inner sleeve $\frac{9}{16}\times3\frac{1}{16}\times3\frac{1}{16}''$, 3″ sq. card, and 15-ft. cloth leader.
RR-9/U		182–212	Both	1	0.35	250	$28\frac{1}{2}''$	$\frac{1}{8}$	0.00035 soft	
RR-18/U		182–212	Both	4	0.9	660	$28\frac{1}{2}''$	$\frac{1}{4}$	0.0009 hard	Strips stacked in three layers in form of foreshortened S.
	CHB-1	193–224	Both	1	0.35	250	27″	$\frac{1}{8}$	0.00035 soft	
RR-16/U	CHA-25-(3)	320–600	Both	3	0.64	3 × 2,400	$15\frac{1}{2}''$ 12, 10″	0.060	0.0009 hard	
RR-11/U	CHA-2-(3)	335–390	Both	3	0.23	2,200	$15\frac{1}{2}''$	0.060	0.0009 hard	
RR-4/U	CHA-28-(3)	450–600	Both	3	0.32	2 × 3,000	$11\frac{1}{2}''$ 10″	0.045	0.0009 hard	
RR-5/U	CHA-3-(3)	520–600	Both	3	0.19	3,600	10″	0.045	0.0009 hard	
RR-19/U	CHA-35-(3)	600–875	Both	3	0.45	2 × 6,000	$8\frac{1}{8}''$ $7\frac{1}{8}''$	0.045	0.0009 hard	
RR-8/U	CHA-4-(3)	660–770	Both	3	0.25	6,000	$7\frac{7}{8}''$	0.045	0.0009 hard	
RR-20/U	CHA-45	860–3,000	Both	1	0.35	4 × 6,000	$5\frac{1}{2}''$ $4\frac{3}{16}''$ $3\frac{3}{16}''$ $2\frac{3}{8}''$	0.035	0.0009 hard	
	CHA-5-(3)	2,700–3,400	Horizontal	3	0.6	60,000	$1\frac{27}{32}''$	0.045	0.0009 hard	
RR-6/U		2,700–3,400	Both	2	0.5	50,000	$1\frac{27}{32}''$	0.045	0.0009 hard	Paper backing glued ¼ to ¾ of length.
RR-7/U		2,700–3,400	Horizontal	1	Net 90±5g	20,000	$1\frac{27}{32}''$	0.045	0.0009 hard	Load for 60-mm mortar shell (T-15, 16, 17).
RR-10/U		2,700–3,400	Horizontal	2	Net 150±5g	35,000	$1\frac{27}{32}''$	0.045	0.0009 hard	Load for 81-mm mortar shell (T-22).
RR-24/U		2,700–3,400	Horizontal	½	Net 45±2.5g	10,000	$1\frac{27}{32}''$	0.045	0.0009 hard	Load for rifle signal grenade (T-62).
	CHW-5	2,500–3,200	Horizontal	¼	0.35	5,000	2″	0.020	0.006 soft	Used for identification purposes.
RR-12/U		8,000–	Both	1	2.5	100,000	$\frac{9}{16}''$	$\frac{9}{16}$	0.00035 soft	

*All strips longer than 20 in. were flat; all shorter were crimped.

the order of $\frac{1}{18}$ in. proved most practicable. Embossed foil is superior to plain foil of the same thickness. The use of a thinner foil or a narrower width tends to increase the birdnesting. In a bundle of 6,000 dipoles, of length frequency to the half-power point is approximately ±7 per cent in material of the present ratio of length to width.

The upper limit of frequencies practical for Chaff is determined by polarization of the

SECRET

radar. Tests have shown that for Chaff dipoles several inches or more in length the orientation in the air after release is approximately random. Shorter dipoles, of the order of 3 in. in length or less, tend to fall in a horizontal position. As a consequence, when such h-f Chaff is observed by a radar in vertical polarization at a moderately low elevation, the responses are negligible as compared to those in horizontal polarization. For that part of the radar spectrum where the lengths of the dipoles are of the order of 2 in., a special type of Chaff has been devised to overcome this difficulty. A thin paper backing is used but it is glued only to one end of each dipole. As a consequence, the unattached end of the tissue backing acts similarly to the feather on an arrow in orienting the dropping dipole vertically. This S-band Chaff is known as RR-6/U (Figure 4). The imperfections and irregularities in manufacture are such that the horizontal and vertical responses from RR-6/U are approximately equal.

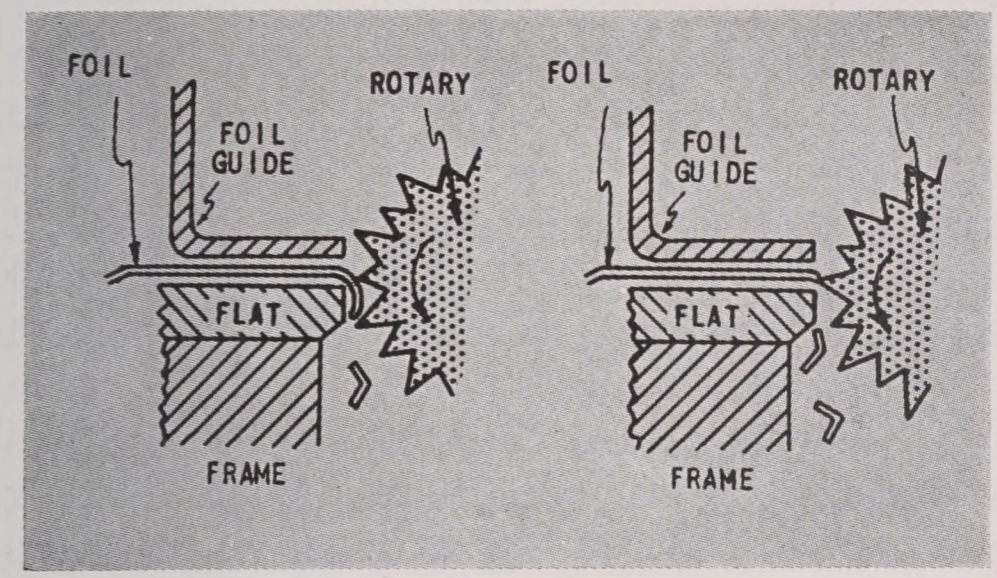


FIGURE 1. Chaff cutter: cross-sectional view of cutting blades showing bending and cutting operations.

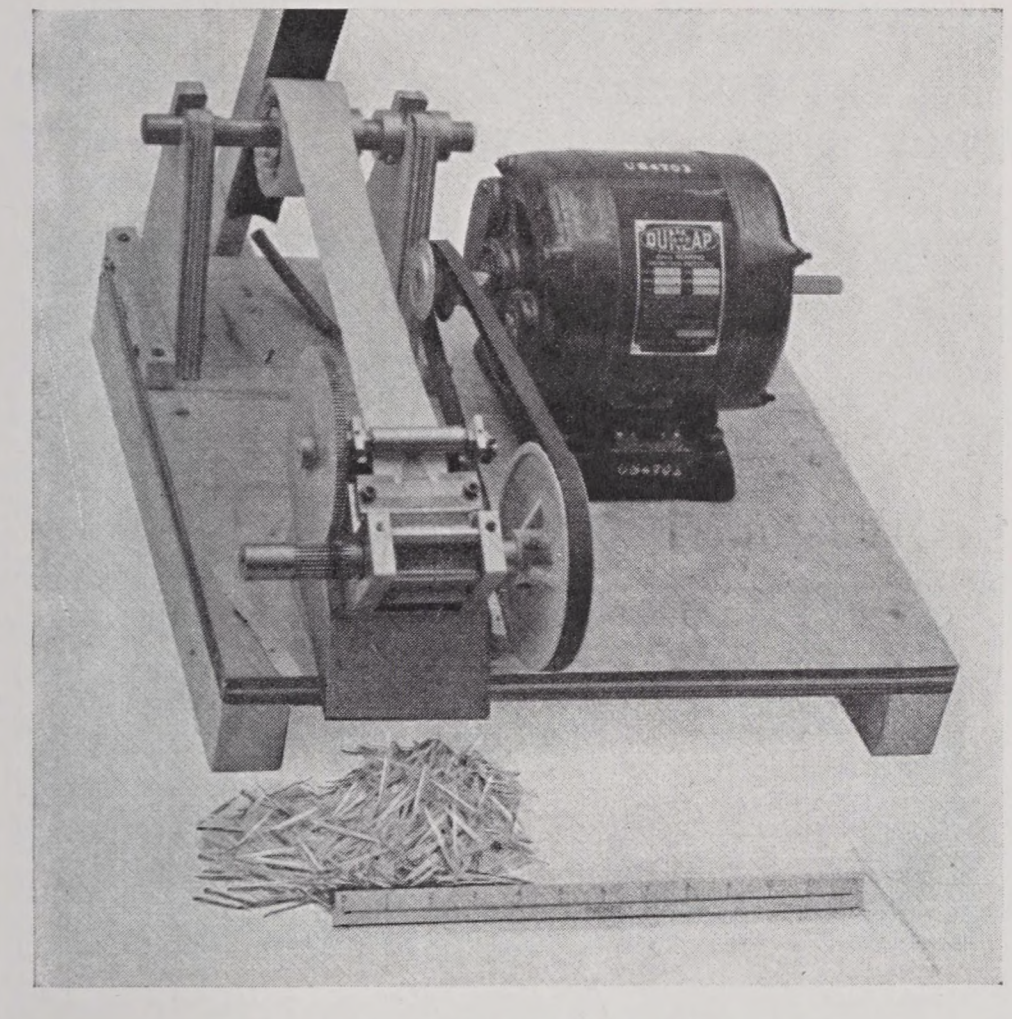


FIGURE 2. The first Chaff cutter.

At higher frequencies, however, where the dipole length is shorter than an inch, the method of manufacture utilized for S-band Chaff becomes difficult and the desired effect has not been obtained by any known type of Chaff in which half-wave dipoles are used. The upper limit, therefore, for unpolarized resonant Chaff is of the order of 5,000 mc. At frequencies possibly up to 30,000 mc, Chaff is still fairly economical as regards weight and volume but will respond only to horizontal polarization. The use of longer Chaff, utilizing the resonance at multiple frequencies, however, has not been fully explored in this frequency region. The Chaff technique developed to date is thus applicable in the radar frequency band from approximately 300 to 5,000 mc for all polarizations. Weight and volume considerations, however, vary considerably over this range. A few simple applications of elementary theory will show how this variation occurs.



FIGURE 3. RR 4/U (CHA-28-3) Chaff used against the Wurzburg band (450-600 mc).

For convenience, a unit of Chaff or Window has been defined as a quantity sufficient, at the resonant frequency, to give a radar echo equal to that of a B-17 airplane seen head on. This

definition is theoretically unsatisfactory and practically impossible to measure with precision but has proved exceedingly useful in practice. Theoretical considerations show that the number of dipoles required to produce a constant effective echoing area varies as the square of the frequency. Because the effective echoing area of an aircraft is not highly dependent upon frequency and because the dependency is not well known, it may be assumed that over the present radar spectrum a unit response corresponds to a constant echoing area (about

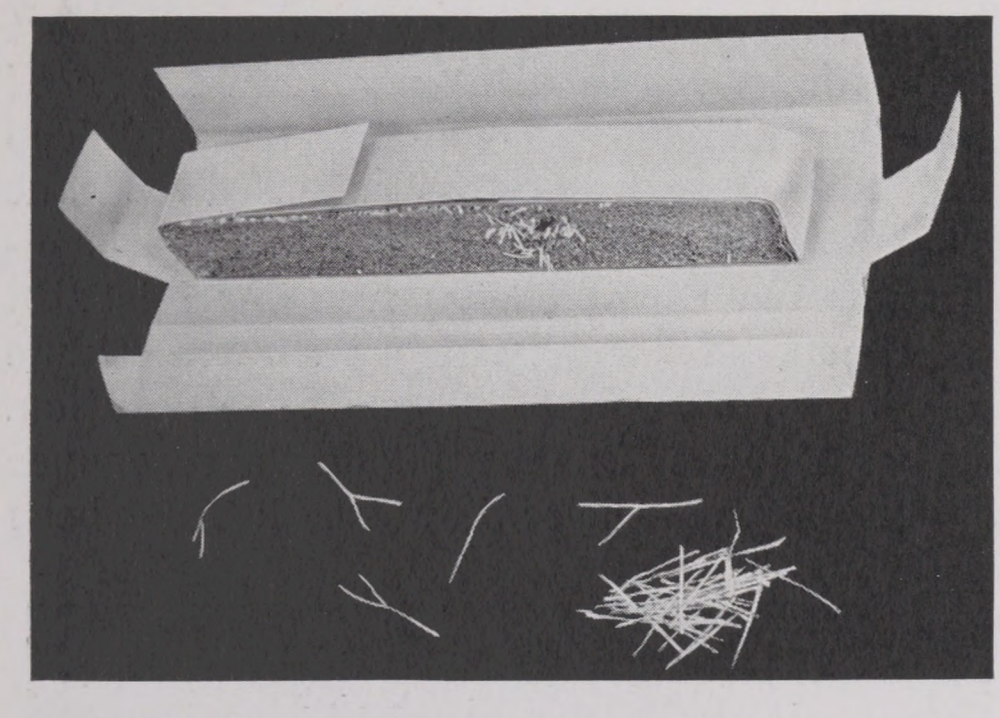


FIGURE 4. RR 6/U half-glued Chaff for use in both polarizations against the 2,700- to 3,400-mc band.

500 sq ft). This assumption is certainly not precise but may be adopted for purposes of discussion. Consequently, the number of dipoles per unit varies as the square of the frequency. The length of the individual dipole varies inversely as the frequency. If Chaff could be made from a material of constant thickness with a constant ratio of length to width, it is clear that the weight of a single dipole would vary inversely as the square of the frequency. The weight of a unit of Chaff would then be independent of the frequency. It has proved impossible, however, to build Chaff that follows this relationship. At higher frequencies the width of the dipoles would be exceedingly small and the birdnesting excessive. Practically, therefore, the width of the dipole decreases only slightly with decreasing length and the weight per unit increases nearly as rapidly as the frequency. The volume of a bundle, however, increases somewhat more slowly than the weight.

In view of the circumstances outlined above, it is fortunate that the German Wurzburg radar system happened to lie in the 450- to 600-mc band, the optimum frequency band for Chaff.[571] As a result it was possible to manufacture Chaff with a weight of only 1 oz per unit for a 13 per cent bandwidth. Early British Window or flat Chaff, cut by guillotine from flat strips, weighed 27 oz per unit and covered only approximately twice the frequency bandwidth of bent Chaff. Improvements by the British, however, finally brought flat Chaff into competition with bent Chaff as regards weight and volume.

Extensive testing and experimenting have led to a triangular sleeve-type of self-opening bundle for Chaff 7 in. or more in length (Figure 3). A simple roll of paper, although fairly satisfactory, is much more difficult to load properly without damaging the Chaff and also gives somewhat greater birdnesting. A flat bundle (Figure 5) is also fairly satisfactory but suffers from the same difficulties as the simple roll and is proportionally heavier. All types of

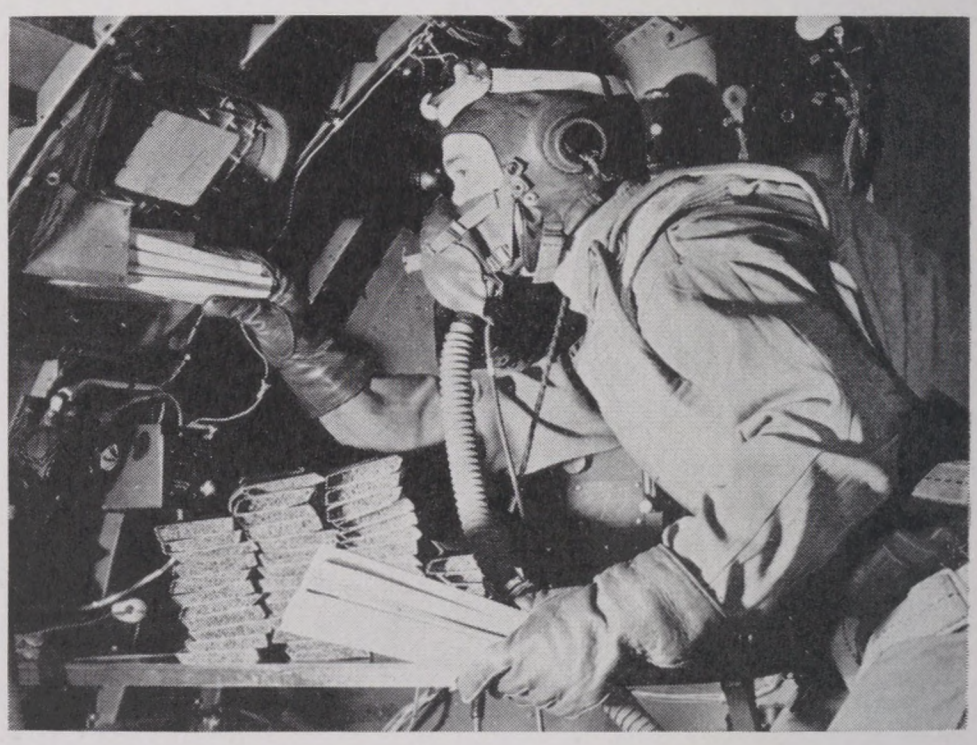


FIGURE 5. Radio operator of B-17 dispensing CHA-3 through chute in window of radio room.

bundles for hand dispensing from aircraft are unsealed. When mounted on double tapes for automatic dispensing, the seal is automatically broken on release from the tape (for dispensing techniques and equipment see Chapter 14). For short Chaff, such as RR-6/U, a narrow box-type bundle is required (Figure 4). A box with closed ends prevents the small dipoles from

SECRET

leaking out as they would from the open-ended triangular type of package. The technique of manufacturing the short Chaff does not permit easy packaging in a triangular or cylindrical bundle.

12.2.3 Flat Chaff

The electrical theory for flat Chaff is identical with that for bent Chaff. The distinction between the two rests chiefly in the technique of manufacture. Flat Chaff is almost universally cut from paper-backed aluminum foil. The use of paper instead of foil for the fundamental strength permits the use of much thinner foil, generally 0.00035 in. in thickness. Where the source of aluminum foil is limited, as was the case in the United Kingdom, the slight saving in foil may be worth while. Furthermore, flat Chaff is cut by guillotine-type paper cutters which are commonly available in almost all establishments that fabricate or use large quantities of paper. Production of flat Chaff can be carried out by any of these companies without special training of the already skilled guillotine operators; unskilled labor can do the work of packaging.

The guillotine cuts flat Chaff from a stack of sheets of paper-backed aluminum foil. The width of each cut is controllable to approximately $\frac{1}{32}$ in., the precision being dependent upon the skill of the operator and the vintage of the guillotine. Widths less than approximately $\frac{1}{8}$ in. are difficult to control with a guillotine and widths of $\frac{1}{4}$ in. or more are considered desirable by members of the trade. Flat Chaff used by the Germans was aimed at a width of 2 cm but frequently deviated from this width by 50 per cent.

The original flat Chaff, some 2 cm in width, was rather inefficient per unit weight because of tearing, birdnesting, and unnecessary width. During the fall and winter of 1943 the British adopted to some extent the production of American-type Chaff and simultaneously set about improving their flat Chaff. Having established their production method on the basis of machinery and techniques available in England, they found it more convenient to continue largely with their original type of production method. The use of narrower strips, of the order of $\frac{3}{16}$-in. width, with more suitable paper backing, and a reduction in the number of strips from 2,000 to 500 per bundle resulted in a marked increase in efficiency of British flat Chaff. Large quantities of this flat Chaff were used by the American Air Forces in the United Kingdom when transportation difficulties led to shortages of American Chaff.

The lower frequency range in which flat Chaff can be used is limited by the length of the standard guillotine cutters, 60 to 72 in., and, more vitally, by the problems of dispensing and birdnesting. A length of 70 in. corresponds to 80 mc. The physical manipulation of Chaff strips of this length is obviously extremely difficult in an aircraft but can be carried out if necessary. The folding or bending of bundles of long Chaff results generally in serious tearing or in birdnesting. It may be concluded, therefore, that for special problems 80 mc is approximately the lower limit for flat Chaff but that a more practical lower limit occurs around 150 mc. Were no other type of Window possible for these low frequencies, flat Chaff could be utilized, but since Rope operates rather well in these ranges it is generally to be recommended.

At extremely high frequencies the greater width of flat Chaff reduces efficiency as compared to bent Chaff, although both the British and the U. S. Navies produced rather heavy types of flat Chaff usable against horizontal polarization in the 3,000-mc region.

To summarize briefly, flat Chaff can be used conveniently in the frequency range from 150 mc to perhaps 5,000 mc, and, although perhaps twice the weight and bulk of bent Chaff per unit over the same frequency band, it can be made with normally available equipment. The best developed type of British flat Chaff is slightly more economical in the use of aluminum foil. Although comparative tests of flat Chaff against bent Chaff have not been exhaustive, there are indications that the individual strips of flat Chaff are more effective than those of bent Chaff in a ratio of perhaps 8 to 5. Probably a physical distortion in the air leaves a permanent bend in the aluminum

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strip, whereas the paper-backed flat strip tends to recover because of its greater pliability. This characteristic, combined with the somewhat greater frequency band of response given by flat Chaff and the somewhat less birdnesting, tends partially to equalize the two types with regard to weight and volume per unit, leaving only the factor of two. Flat Chaff, however, drops 30 to 50 per cent faster than bent Chaff.

Changes in humidity cause a marked curling effect in flat Chaff made from a sheet of aluminum mounted on a single sheet of paper. To eliminate this curling effect, flat Chaff manufactured for the U. S. Navy is designed as a sandwich of aluminum foil between two sheets

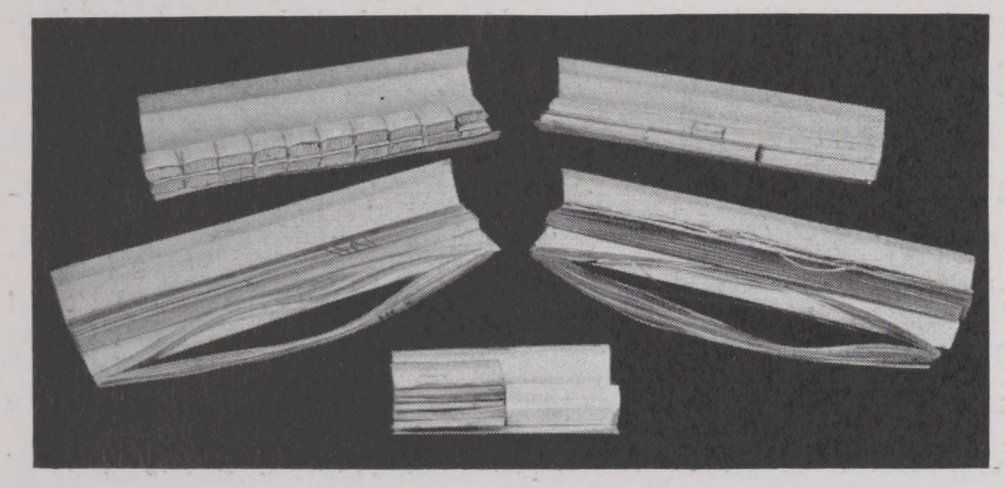


FIGURE 6. Various types of U. S. Navy flat Chaff.

of tissue paper. Humidity changes set up equal strains on the two sides of the individual strip and curling is reduced to negligible proportions. Aside from somewhat greater difficulties in manufacture because of extra lamination, this type of Chaff is superior to the flat Chaff made with only one sheet of paper. Humidity controls were very strictly observed in the production of British Window to reduce the curling phenomenon. It is possible that the very poor quality of paper used perforce by the British was largely responsible for the success of their flat Chaff. The paper was only one order better than our blotting paper, with so low a tensile strength that curling from humidity changes was greatly reduced. Test quantities of flat Chaff cut from American bond paper of normal quality performed badly.

In the manufacture of flat Chaff, the U. S. Navy exploited a very practical method to prepare for unknown enemy radar frequencies in distant theaters of action. For this purpose their flat Chaff was cut in two standard lengths, 20 in. and 60 in. The dipoles, however, were connected at both ends by the seal that was originally placed at the ends of the stack of sheets from which the dipoles were cut (Figure 6). The handling of the Chaff stacks was expedited greatly by the seals but the Chaff could not be used until the ends of the packages were cut. In field operations, after the enemy frequencies had been ascertained by Ferret missions, small hand-operated guillotines were used to cut the Chaff (including the cardboard bundle) to length. These guillotines are simple in operation, can be easily sharpened, and a few of them are capable of cutting the ends from large quantities of Chaff. Contingencies with regard to enemy radar frequencies can be dealt with easily in the field without the complication of elaborate manufacturing plants. Such a Chaff procedure, useful to the U. S. Navy in the distant Pacific Theater where enemy frequencies could not be anticipated, would not have proved useful to the U. S. Army Air Forces in the European Theater of Operations, where extremely large quantities of Chaff were needed for a specific frequency band.

It is of general interest that all types of paper-backed Chaff, both bent and flat, that are packed longitudinally in paper or cardboard bundles can be cut to shorter lengths by hand-operated guillotine machines without serious damage to the strip. In the case of Chaff made from pure aluminum without paper backing, a certain amount of welding occurs at the end where the cut is made and the birdnesting is somewhat increased. Nevertheless, it is generally possible to cut Window to resonate at a higher frequency, without complicated equipment, in the field.

British Window was almost universally packaged in a roll-type bundle. The U. S. Navy flat Chaff was packaged in a light cardboard wrapper as shown in Figure 6. German flat Chaff, dimensions 2x80 cm, was held in bundles of several hundred strips by means of two sealed paper bands that break in the slip stream of an aircraft. Tearing and birdnesting from the German-type Window is quite excessive. There was also some question as to the formula used by the Germans in calculating the length of

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the dipoles. Strips 80 cm long correspond to a frequency of approximately 177 mc, not resonant with any of the British radars against which the Chaff was presumed to operate. The tearing was so great, however, that the Chaff resonated rather well at almost all higher frequencies, including the S band. It must be noted in this connection that such a method of obtaining wide-band response from Window is not economically sound, although it may occasionally be useful under the pressure of circumstances.

The physical awkwardness of l-f flat Chaff, especially for automatic dispensing, constituted a long-standing problem. In the spring of 1945, however, a solution was obtained which appears to offer promise. Flat Chaff was made for the 182- to 212-mc band by using relatively heavy hard foil (0.0009 in.) backed on both sides with light paper (15-lb tissue). Three layers of 220 strips ¼x28½ in. were each folded in the form of a foreshortened S (Figure 7). The birdnesting with this type of bent Chaff was only about 20 per cent soon after the Chaff was packed. In about 10 weeks, however, the birdnesting increased from 20 to 35 per cent. Because of the end of World War II, further aging tests were not conducted. However, it is possible that the "set" of the paper might increase the birdnesting still further and also reduce the effectiveness of the dispersed dipoles.

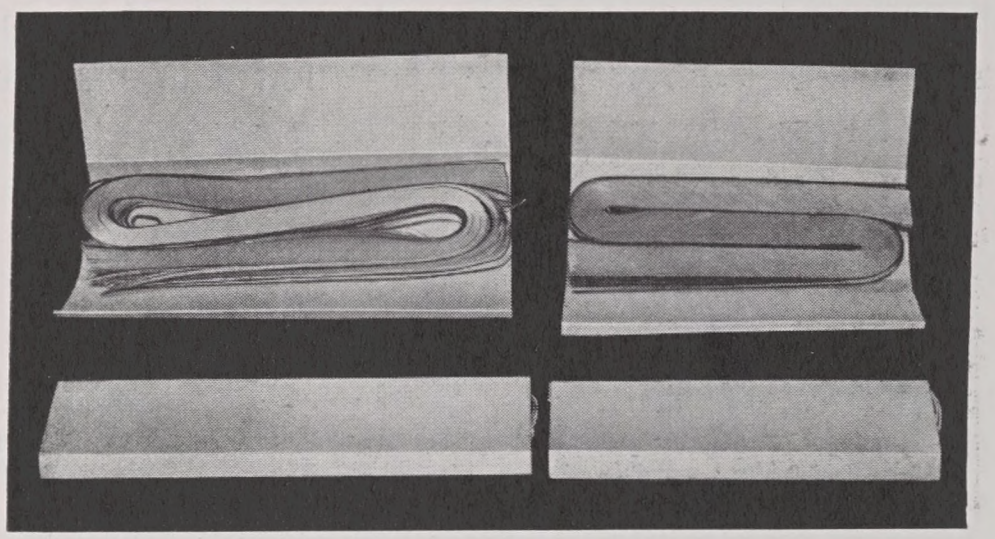


FIGURE 7. Low-frequency Window packaged for mounting on double tapes for automatic dispensing.

12.2.4

Tuned Rope

Although never produced in quantity for countermeasure purposes, tuned Rope[375] may excel in two types of problems:

1. Where it is desirable to maintain a reflector for a long period of time, e.g., a balloon-supported reflector for meteorological purposes.
2. Operation against a vertically polarized system over a frequency band too low for the efficient use of Chaff and too narrow to justify the heavier untuned Rope (see Section 12.2.6).

At low frequencies and vertical polarization, tuned Rope theoretically should be much lighter per unit than untuned Rope or Chaff of the types already developed. Practically, however, no successful tuned Rope has been developed at low frequencies. A natural medium to support the dipoles is paper, which can be easily fabricated into neat compact rolls and unrolled automatically on release from an aircraft. An example of such a tuned Rope is shown in Figure 8. The dipoles were glued to a continuous roll of paper in wide sheets of the correct length by the laminating machinery used in the foil industry. The larger rolls were then slit into narrow rolls, each of which was attached to a parachute-opening device. Drop tests from aircraft uncovered a fundamental difficulty that has not yet been solved for tuned Rope using a paper medium. The set of the paper in the small roll causes the Rope to rewind into a compact tangle. The use of a heavy core might be practical against a system with only vertical polarization but would increase the rate of fall unduly. It is possible that a cellophane[c] or, better, some similar thin supporting medium could be used instead of paper; further experimenting might prove fruitful in developing this type of tuned Rope.

Theory indicates that the response per unit length of tuned Rope is not highly sensitive to the distance between the ends of the dipoles. A mass production method of breaking the electrical contact at suitable intervals along a continuous roll of foil laminated to some medium, such as paper, might produce a very satisfactory type of tuned Rope even though the breaks are small compared to the length of dipoles.

[c] Cellophane has proved to be unsatisfactory as a foil backing because of its elasticity and sensitivity to humidity changes.

With 0.00035 in. thick foil a 110-v current across contacts separated by a distance of the order of ¼ in. will burn off the foil without damaging the paper backing. This method is undoubtedly capable of development for mass production but has not been pursued because of the difficulties enumerated above in actual operation. The method, however, has been further developed for removing the metallic tinsel from the tinsel wire used as a flexible conductor in telephonic devices.

Tinsel wire consists of a thin and narrow metallic ribbon wound spirally about a thread. When the thread is constructed of glass, the tensile strength is surprisingly great, sufficient to support a spool of several thousand feet. In the present fabrication of tuned Rope from tinsel wire, the metal of the wire is removed at

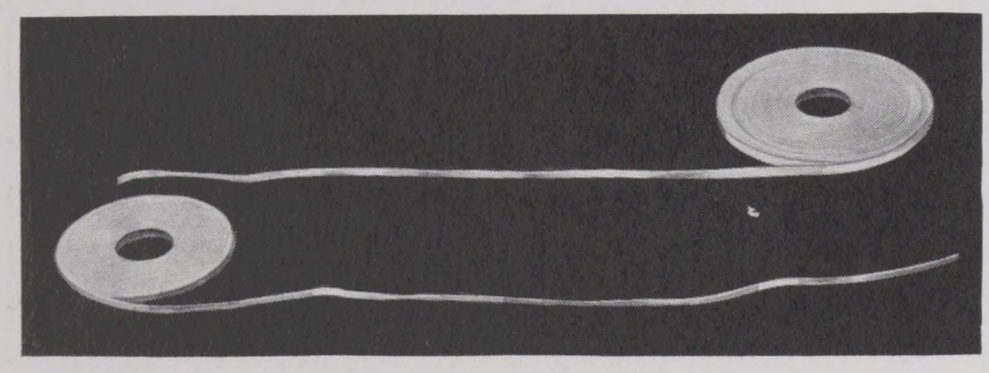
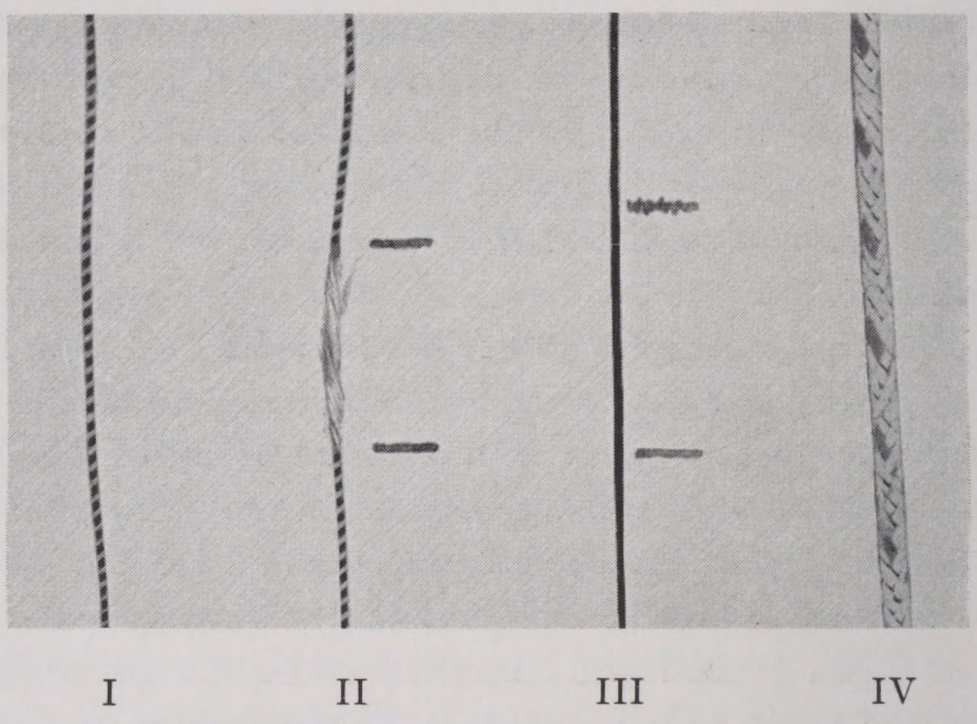


FIGURE 8. Tuned Rope.

intervals by passing the wire over a fixed pair of contact points which are electrified at uniform intervals or by passing the wire over a wheel on which are located several properly spaced pairs of contact points. The use of an air blast to remove vaporized metal from the contact point has made the rotary-wheel system promising as a mass production device.

If the tuned Rope made from tinsel (Tinsel Rope or Fishline) is to be used more than once, it can be run into a braiding machine or covered with a lacquer in order to prevent the glass thread from fraying. If the Fishline is to be used only once, as a countermeasures device, the sparked tinsel thread can be used directly (Figure 9).

Tinsel Rope tuned for the S band proved moderately successful when woven into a standard target sleeve for use against an S-band *gun-laying* [GL] radar system. Development of the material as a reflector on meteorological balloons and possibly as a countermeasures device is incomplete but shows some promise. Tinsel Rope has the advantage of relatively light weight, extreme compactness, and simplicity of manufacture, once production machinery has been developed. Its operational effi-



I II III IV

FIGURE 9. Tinsel (Fishline) Rope. I is tinsel before firing, II is tinsel after firing, III is fired tinsel covered by lacquer, and IV is fired tinsel covered by braiding.

ciency, however, deserves much more thorough evaluation. It may be used at any point in the radar spectrum, conceivably to 30,000 mc, but more probably to 10,000 mc.

12.2.5 Turnstiles

A priori, thin wires might be expected to compete favorably with Chaff, particularly at higher frequencies where birdnesting might appear not to be serious. As a matter of fact, a few elementary calculations will show that wire in dimensions that are practical operationally is both heavy and voluminous as compared to Chaff. An aluminum wire of diameter of only 0.010 in. corresponds in cross section to a foil strip 0.10 in. wide and 0.0008 in. thick. The wire has the added disadvantage of a rapid rate of descent and a much reduced bandwidth of frequency response.

It becomes apparent, therefore, that wire is desirable as a form of Chaff only when a rapid fall is desired and when the weight of the single unit is not of great importance. Such a set of conditions arises when reflectors are to

be used in small quantities for identification or signaling purposes, for example, in ground-controlled approaches of aircraft where many aircraft are involved and where misidentification is apt to occur. An aircraft in radio communication with the control radar on the ground may, upon request, identify itself by dropping Window. Rapid-falling Window is obviously desired in order that clutter may not

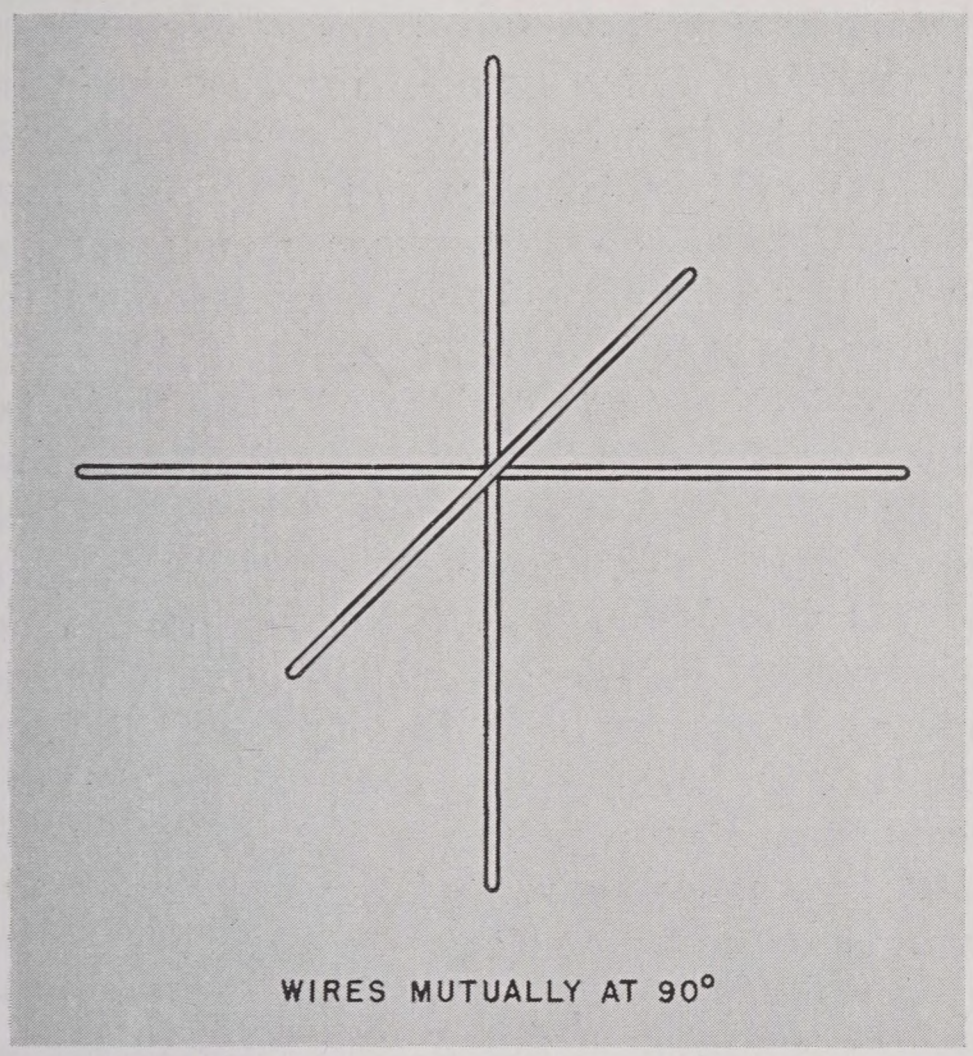


FIGURE 10. Turnstile. Wires are mutually at 90°.

interfere with the controlling radar. The method has been tried but not adopted for general use.

In certain spoof operations a fast-dropping Chaff is desirable in order that the Chaff may drop quickly out of the radar lobe. A long formation of aircraft may thus be simulated. In this operation, however, the weight of wires and their narrow frequency band of response constitute a marked disadvantage.

It has been reported that Turnstiles, made from three half-wave dipoles of wire held mutually perpendicular at the centers, have been tested as reflectors on tow-targets and balloons with mediocre success. Turnstiles (Figure 10) are relatively difficult to manufacture, cannot be packaged compactly, and fall very rapidly. Their usefulness as a radar countermeasure appears to be exceedingly limited if, indeed, they can be used effectively at all.

12.2.6 Rope

Untuned Rope, as it has been produced in quantity, consists of rolls of 0.0009-in. foil ½ in. wide and 400 ft long (the British have used considerable quantities in 200-ft rolls). These rolls are roughly 3 in. in diameter and packaged three to a bundle. Two types of opening devices have been used, a small paper parachute or a simple card each attached to a 15-ft leader tape of rayon or cotton ribbon (Figure 11). The long leader strip was found necessary to insure that the card or parachute would remain attached to the foil streamer in the slip stream of an aircraft.

Before opening tests had been conducted it was visualized that the streamer would hang vertically below the parachute after unrolling. This expectation was far from the truth. The forward motion of the foil roll first unwinds the streamer in a nearly horizontal position during the first seconds after the roll enters the slip stream. The roll then decelerates because of the air resistance, finally unwinding in a downward direction. Both the parachute and the card are then apt to fall more rapidly than the central portion of the streamer so that in many instances the streamer appears as an inverted parabola approximately ½ to 1 min after it opens. The curve of the streamer, however, is quite irregular and distorted.

When a parachute is employed, the response in vertical polarization tends to be 2 or 3 db greater than in horizontal polarization. However, when a core is used, the response is about equal in both polarizations.

If the central core drops off, the streamer is much more irregular than if the core remains attached. The streamer with a detached core tends to tangle and bunch at the lower end; radar tests indicate that a slightly greater horizontal component of reflection occurs in this instance than when the core remains attached. Cores have generally remained attached because the rolling process of manufacturing is

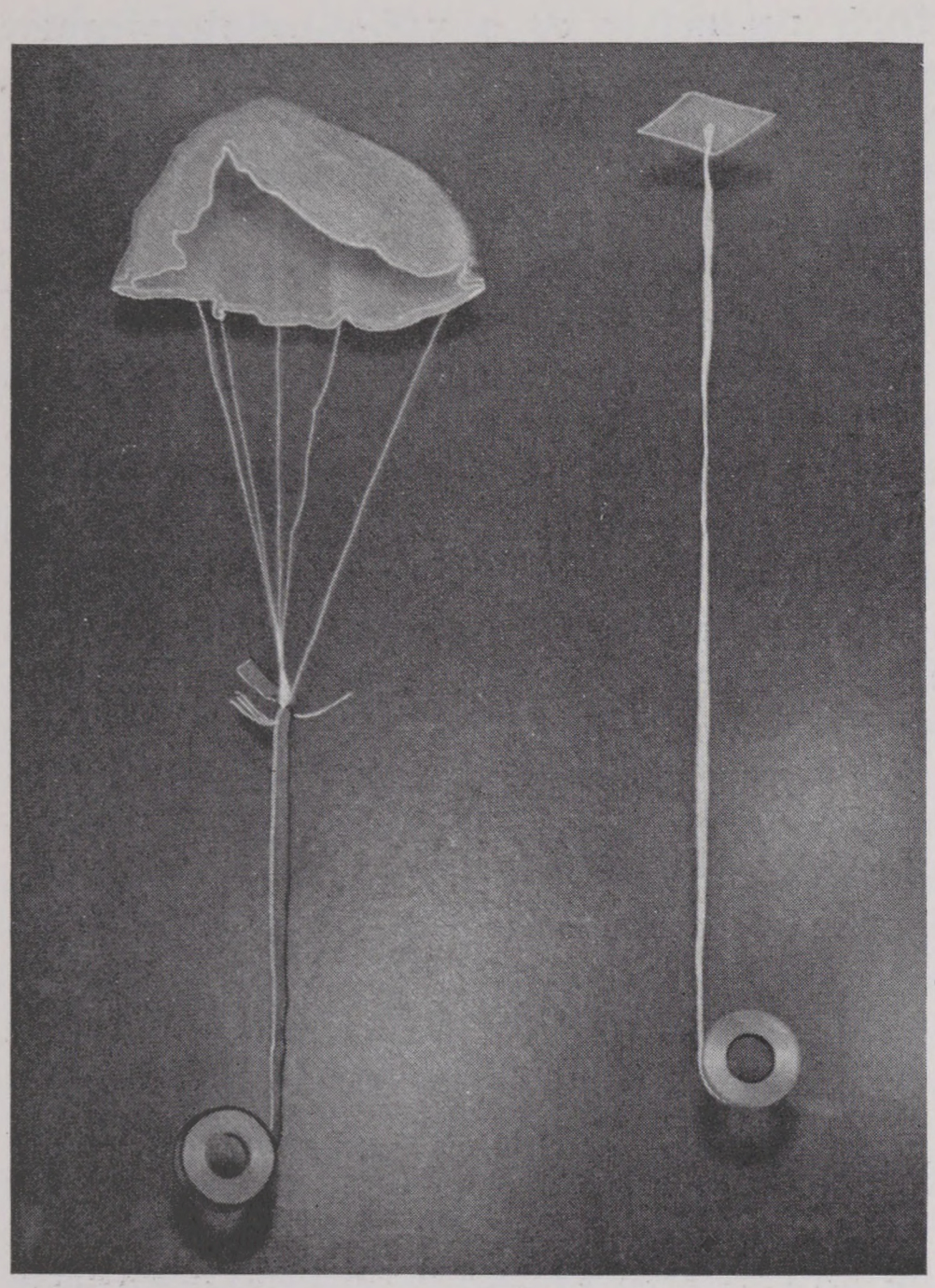


FIGURE 11A. Untuned Rope for use against frequencies below 350 mc. Two types of opening devices are shown, a small paper parachute and a simple card.

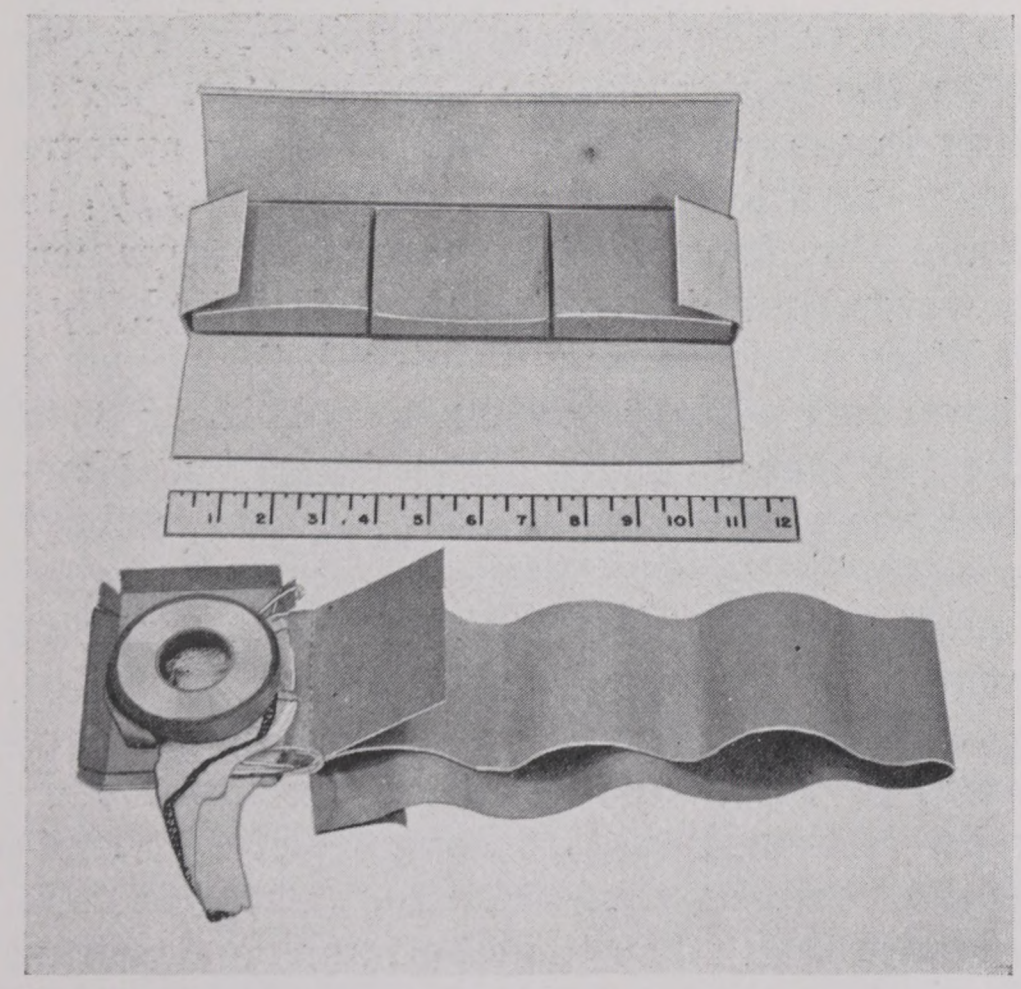


FIGURE 11B. Untuned rope for use against frequencies below 350 mc, here shown packaged.

simplified by gluing the foil to the core. The operational difference between the two types is small. More recent tests have shown that simple foil rolls without leader strip, cards, or inner sleeves are nearly as effective against 100-mc horizontal polarization as is standard Rope. More complete testing is needed, however, to demonstrate without a doubt that such a change is justified. The simplification in manufacture would be considerable and justifies much more testing in case large quantities of Rope are to be produced. Some gain in response could be obtained by insuring that the core of the roll will fall off the streamer. It is important that the optimum balance between manufacturing cost and performance be attained before establishing specifications of Rope.

A reduction in the width of Rope to ¼ in. and a reduction in thickness to 0.0006 in. show a theoretical factor of gain of 2 in weight and value. Practically, however, the theoretical gain of 500 was attained at 200 mc on horizontal polarization but not at 100 mc. As a consequence, it appears likely that minor production improvements in ½-in. Rope may be more economical than a change to ¼-in. Rope.

The response characteristics for Rope have been measured empirically from about 75 mc up through the S band. The theory of the response is complex, but a first approximation indicates that a bundle of Rope equals approximately one unit at 200 mc, responds with increasing efficiency at lower frequencies, and tapers off in effect at higher frequencies. At 200 mc, in the Wurzburg band and in the S band, the theory is rather well confirmed by observations. The response at 3,000 mc from a bundle of Rope is roughly one-fifth of a unit. The frequency band of maximum efficiency for Rope is known to lie in the region from about 75 mc to perhaps 300 mc and the lower limit may be well below 75 mc. At frequencies above 300 mc, Rope may still be used with considerable effect but its efficiency decreases fairly rapidly with increasing frequency. Under specific operational circumstances, the questions of quantity of Window needed, methods of transport, and dispensing techniques determine the choice of which type of reflector should be used.

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12.2.7

Corner Reflectors

Three mutually perpendicular planes intersecting at a point constitute a corner reflector[461, 150] if the planes are electrical conductors. Wire mesh can be used as the reflecting planes for wavelengths considerably greater than the dimensions of the mesh. Qualitatively, radiation is reflected successively from the three planes back in the original direction, as a handball returns from the corner of a handball court

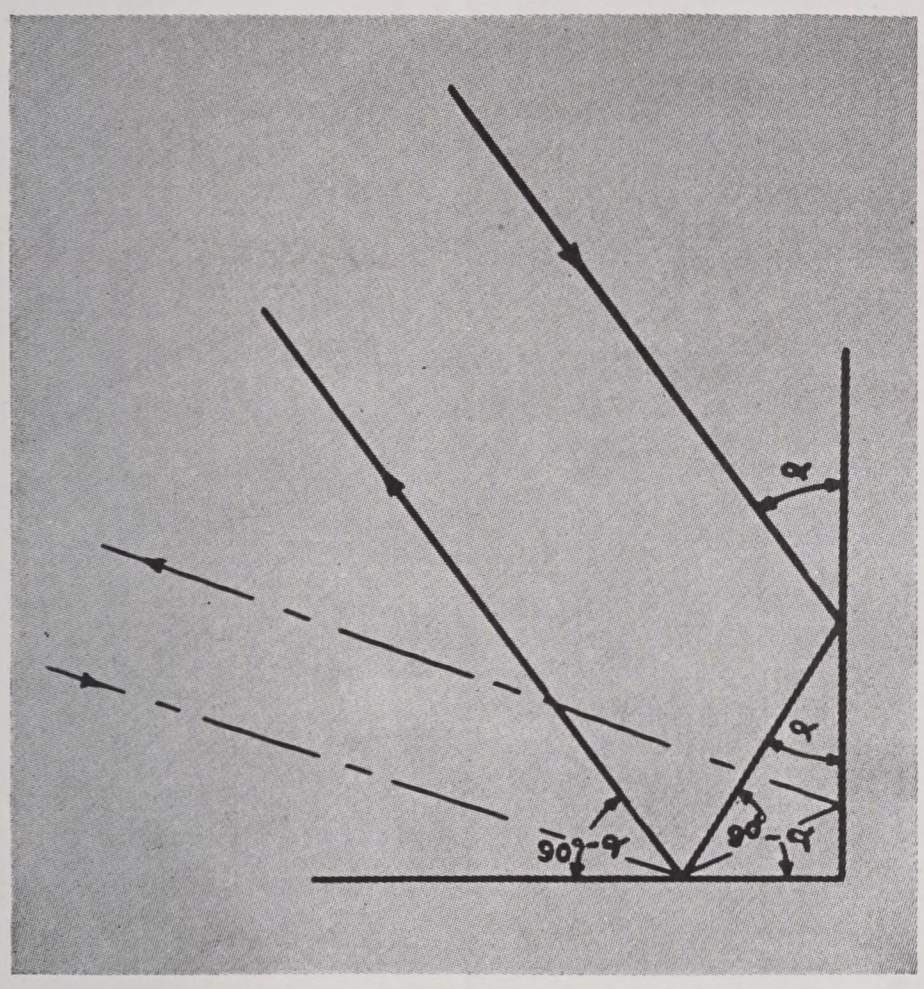


FIGURE 12. Principle of corner reflector.

(Figure 12). More refined theory shows that the effective echoing area of an ideal corner reflector varies as d^4/λ^2, where d is the length from a corner along an edge, λ is the wavelength, and the ratio d/λ is large. Hence, the effective area of a given corner reflector varies as the square of the frequency; at a given frequency, a given type of corner reflector has an effective area proportional to the fourth power of its linear dimensions.

A second theoretical conclusion turns out to be of primary practical importance. If the angles formed by the three surfaces forming a corner deviate from 90 degrees, the equivalent echoing area is reduced. If the error at the tip of each of the three arms is 0.35λ, the response will be decreased 3 db. If it is 0.62λ, a loss of 10 db results. Thus, at 10,000 mc (wavelength of 3 cm) deviations of the outer edges of the three surfaces of about 2 cm ($0.62 \times 3 = 1.86$) will reduce the equivalent echoing area by about 10 db.

To assess the significance of these theoretical deductions in the practical problems of corner reflectors, the specific use and concomitant mechanical design of the corner reflector must be considered. Five classes may suffice:

1. Airborne, self-opening, and free-falling (Kites) to be used as countermeasures.
2. Balloon-supported for countermeasures or meteorology.
3. Aircraft-towed as radar GL targets.
4. Raft- or boat-supported.
5. Ground-based.

Airborne, self-opening, and free-falling corner reflectors were earlier known as Angels and later as Kites. A great amount of effort has been expended in their development. A late

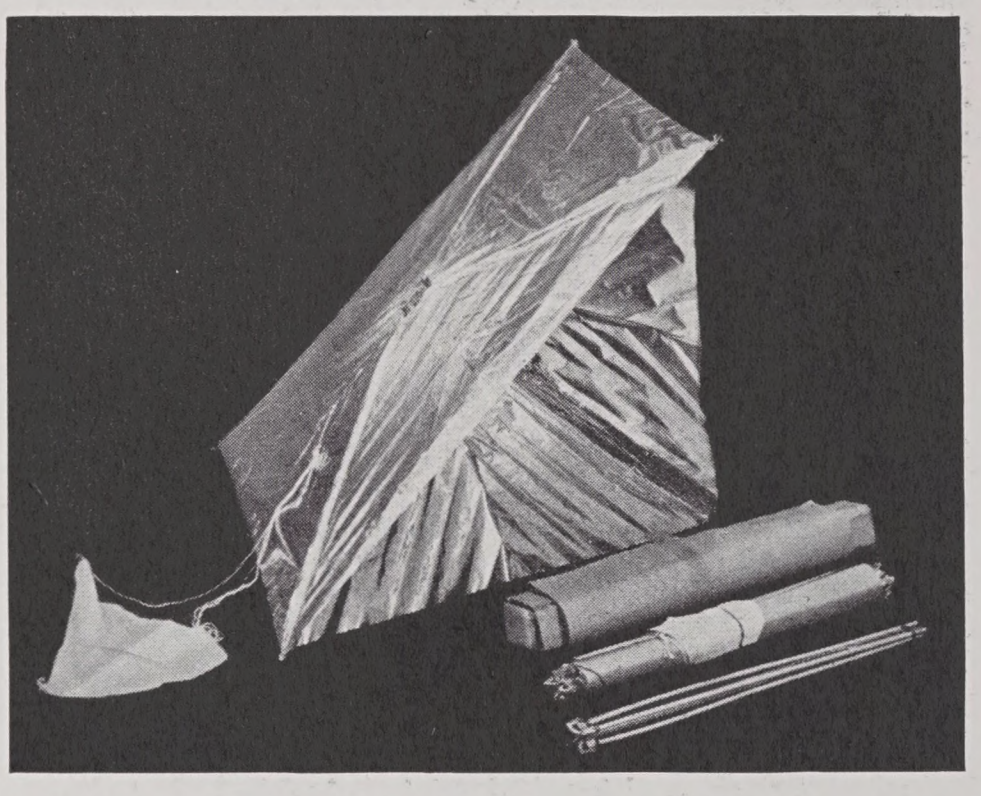


FIGURE 13. Seventeen-inch self-opening Kite (Angel) packaged for dispensing from an airplane.

example is shown in Figure 13. The four-quadrant type is sufficient because reflection below the fundamental plane is usually satisfactory for the purposes of countermeasures. Required characteristics are light weight, compactness, reliability of opening, strength to withstand the shock of opening, ability to orient properly in the air, and, last (and most difficult), maintenance of angular tolerances while falling freely.

SECRET

The principles of the best design for Kites can be seen by inspection of Figure 13. Upon the opening of an outer bundle, a central spring raises the arms, which then support the lacquered foil surfaces. The Kite floats down slowly, acting as its own parachute. All of the required characteristics were attained with reasonable success except for the maintenance of angular tolerances in the air. The most carefully made examples failed by about 10 db in returning the theoretical radar response.

Kites must be designed so that they may be handled conveniently in aircraft. A package length of 3 ft is about the maximum dimension of package which can be tolerated; this fixes the maximum dimensions of practical Kite at about 6 ft. This size Kite should give a unit echo at frequencies in the neighborhood of 3,000 mc.

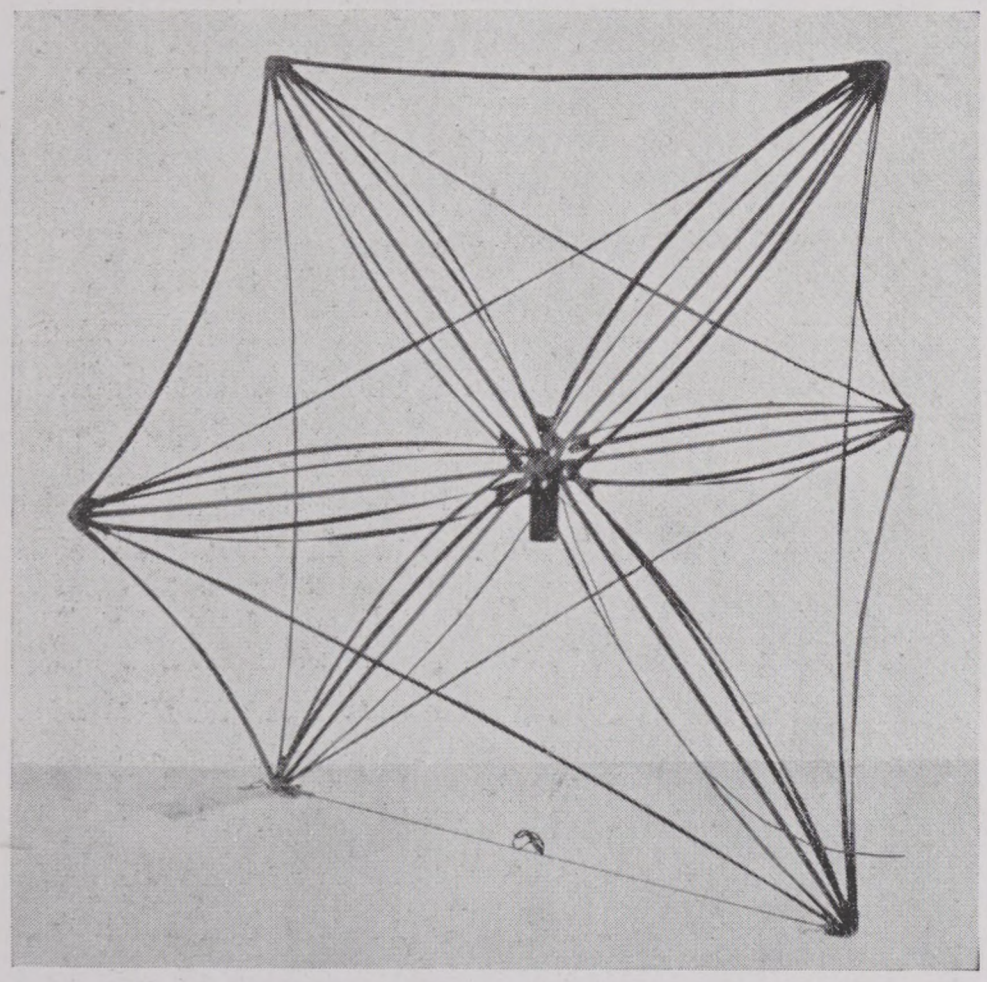


FIGURE 14. Mesh corner reflector for use on a life raft.

Development of a 3-ft Kite was first undertaken but later abandoned because of operating difficulties, bulkiness, and weight. Experience gained from the work on larger Kites was then applied to the development of 17-in. one-half diagonal Kites to operate at 10,000 mc and higher frequencies. The best models failed in radar response by 10 db, as mentioned above. Whether the failure arose largely from the bowing of the foil surfaces during descent, or from the lack of squareness, could not be determined with certainty. A supporting parachute for this type of Kite was found to be impractical, because of the bowing of the horizontal surfaces and because of the fact that the parachute would collapse on top of the Kite because of the slow rate of descent. A parachute might be employed profitably, however, if some type of wire mesh could be substituted for the foil surfaces, but further research on the problem appears to be of doubtful value.

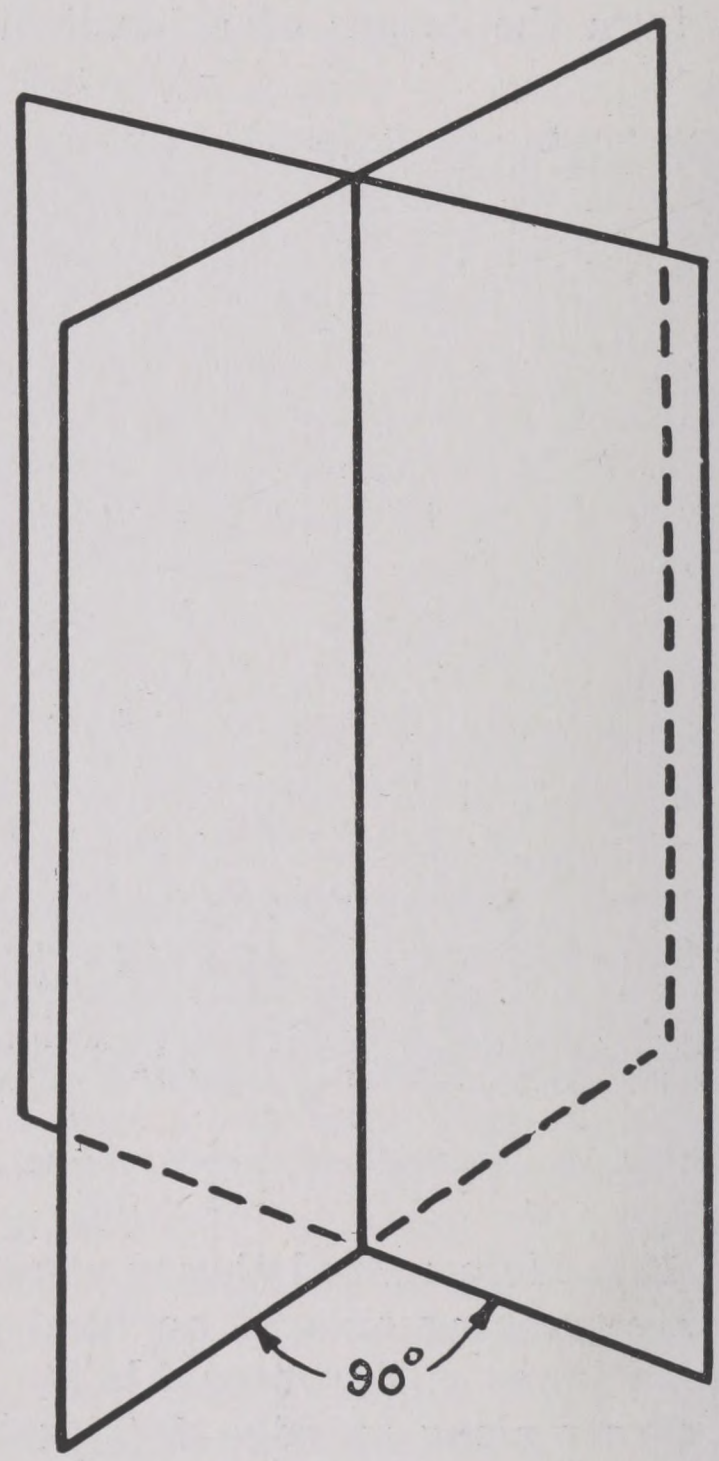


FIGURE 15. Diplane.

Balloon-supported corner reflectors present fewer complications in design than the self-opening free-falling varieties. Four-foot half-diagonal Kites have been used by the United States Navy on balloons attached to unmoored rafts. Corner reflectors carried by free balloons were partially successful for meteorological purposes when used in conjunction with S-band radar systems. Long periods of fadeout intro-

duced serious difficulties, as did low response at great distances.

The problem of maintaining angular tolerances in a lightweight reflector is the most serious one for balloon-supported corner reflectors. This problem must be solved if the response characteristics of a corner reflector are to be satisfactory for radar tracking. covered with wire mesh, and fabric sleeves covered with Tinsel Rope proved less effective. At the crossover point, as seen from the radar, the radar tends to follow the tow-target cable —with consequent danger to the towing aircraft. It is hoped that low-reflection tow-target cable[715] will materially assist in this problem.

Raft- or boat-supported corner reflectors for



Im Westen

Die Angriffe der Royal Air Force auf Deutschland sind nur der erste Abschnitt der britisch-amerikanischen Offensive. An der Vorbereitung des zweiten arbeiten England und Amerika Tag und Nacht.

Im Osten

Die ersten neun Monate des Russenkriegs haben Deutschland mehr Blut gekostet als die vier Jahre des ersten Weltkriegs. Wieviel Blut werden die zweiten neun Monate Deutschland kosten? Die ganze Welt weiss, dass Deutschland den Krieg am Ende verlieren muss.

Kann dieses Gemetzel beendigt werden, ehe es zu spät ist?

Noch einmal hat die britische Regierung durch die Erklarung Lord Cranbornes vom 21. Mai und die Sonderbotschaft von Sir Stafford Cripps vom 11. Mai den Weg hierzu klar und deutlich gezeigt.

- DIE DEUTSCHEN müssen den Krieg, den Hitler um Jahre zu verlängern trachtet, selbst verkürzen.
- DIE DEUTSCHEN müssen die Herrschaft einer Gangsterbande, die Hitler und seine Spiessgesellen Deutschland auferlegt haben, selbst stürzen.
- DIE DEUTSCHEN müssen sich an die Seite der unterdrückten Völker stellen, die alle für die Wiedererrichtung ihres Staates kämpfen, eines Staates, der auf der Achtung vor den Rechten der Völker und des Einzelnen beruht.

Die umstehend wiedergegebenen Erklärungen sind ebenso wie alle ähnlichen Erklärungen britischer Staatsmänner von der Hitlerregierung dem deutschen Volk entweder ganz unterschlagen oder in verzerrter Form mitgeteilt worden.

NACH HITLERS STURZ

Über die britische Nachkriegspolitik gegenüber Deutschland hat Lord Cranborne am 21. Mai 1942 für die britische Regierung folgende Erklärung abgegeben:

EINES der Ziele, für die wir in diesem Krieg kämpfen, heisst Gerechtigkeit. Gerechtigkeit zuerst für die von Deutschland versklavten Völker, Gerechtigkeit für uns selbst, Gerechtigkeit für Deutschland, und harte, unbeugsame Gerechtigkeit für jene Deutschen, die sich der abscheulichen Verbrechen schuldig gemacht haben, deren Zeugen wir waren.

„Die Naziführer können wir nur als Gangsters betrachten. Auf ihr Wort ist kein Verlass. Unsagbare Verbrechen haben ihre Hände besudelt. Solange die Naziführer in Deutschland an der Macht sind, so lange gibt es für Europa weder Frieden noch Gerechtigkeit.

„Die nach dem vorigen Krieg verfolgte Politik ist nicht die Politik, wie sie die Churchill Roosevelt Erklärung festgelegt hat. Die Politik nach dem vorigen Krieg führte, (wenn auch nicht mit voller Absicht), zu Deutschlands wirtschaftlicher und militärischer Bestrafung. Völlig andere Auffassungen leiten die Churchill Roosevelt Erklärung. Aus ihr spricht die feste Entschlossenheit zu verhindern, dass Deutschland oder irgend ein anderer Angreiferstaat jemals wieder imstande ist, eine neue Weltkatastrophe heraufzubeschwören. Es besteht aber keineswegs die Absicht, Deutschland wirtschaftlich zu benachteiligen."

Was dies vom deutschen Volk verlangt, hat Sir Stafford Cripps in einer Sonderbotschaft an Deutschland über den Londoner Rundfunk am 11. Mai 1942 klargemacht:

HITLER gewann seine ersten Siege in Deutschland selbst — gegen die Gewerkschaften, gegen die Kirchen, gegen das deutsche Volk. In Deutschland begann dieser Weltkrieg — und in Deutschland muss er beendet werden . . . Wir sind alle Soldaten einer grossen Armee der Freiheit, die alle Länder umfasst. Die einen tragen Waffen — die besten Waffen der Welt. Die anderen sind unbewaffnet. Aber jeder kann handeln, jeder kann zuschlagen — für den Sieg. Keiner kann neutral bleiben. Jeder muss durch seine Taten zeigen, wo er steht: ob gegen uns und die Freiheit, oder an unserer Seite in der grossen Armee der werdenden Welt."

502

FIGURE 16. Earliest type of British window.

Heavier corner reflectors have been built by the United States Navy to maintain angular tolerances, but they require excessively large balloons.

Aircraft tow-target sleeves have incorporated corner reflectors for radar GL practice. Wire-mesh corners have proved to be the most successful type of reflector for the purpose in the S and X bands. Turnstiles, fabric sleeves countermeasures, for position marking, or for GL targets, must be relatively large to be effective. The problems are generally outside the province of this book and will not be discussed in detail. A mesh of noncorrosive metal is most commonly used. The supporting framework becomes a marine construction problem.

An eight-quadrant collapsible corner reflector designed for life rafts in air-sea rescue

SECRET

work has been manufactured in quantity. It is beautifully designed with monel mesh on a Duralumin frame and die-cast central fitting (Figure 14). Reports suggest, however, that it may be too small to be observed in the S band at a sufficient distance. The half-diagonals are 21 in.

Ground-based corner reflectors can be made with the precision required, since weight is of minor importance. Surprisingly large dimensions are required, however, to simulate cities or groups of buildings for airborne radar deception. Buildings constitute corner reflectors in themselves and as such can be simulated only by corner reflectors of nearly comparable dimensions.

Reflectors used as ground markers usually must be rather large to show through the ground clutter.

Diplanes, constructed from two mutually perpendicular planes of conducting material (Figure 15), are essentially a special case of the corner reflector. They can be substituted for corner reflectors where all angles of radar observation lie nearly in a plane. A typical situation is that of a balloon-supported corner reflector to be observed only at long range and consequent low angle of elevation. Here a diplane hung with its axis vertical would be quite as satisfactory and much simpler in construction.

All problems involving corner reflectors should be investigated carefully for the possible substitution of diplanes.

12.2.8 Squares or Sheets

Sheets of paper-backed foil were the first form of Window to be tested by the British. Rectangular sheets were printed for psychological purposes (Figure 16) in addition to their countermeasures value. None was actually used, however, because of security reasons. It was feared that the enemy would retaliate with Window and seriously weaken the then vulnerable United Kingdom radar chains. Simultaneously, the Germans kept Window completely hidden for the analogous reason.

Sheets of foil [627] do not resonate but act only as mirrors for wavelengths smaller than twice the length of the sheet and as poor scatterers for greater wavelengths. Hence, dipoles are more efficient than sheets by orders of magnitude for frequencies up to approximately 10,000 mc. As Window theory developed, the British quickly abandoned the large sheets for use against the German Wurzburg frequency and developed flat Chaff, which they first used in July 1943.

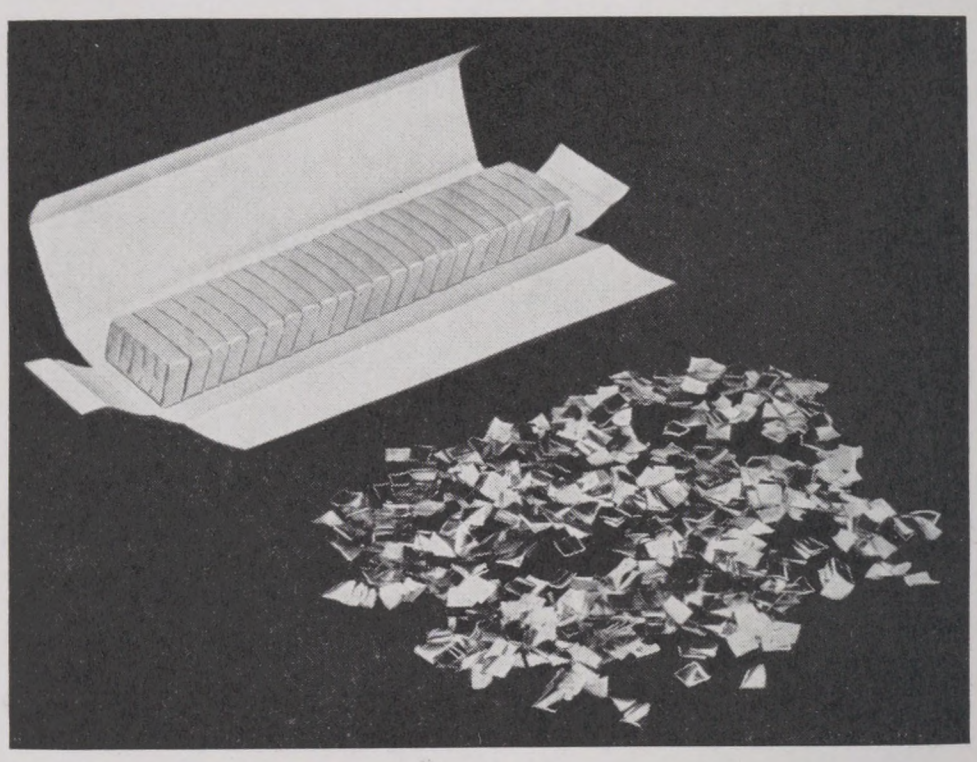


FIGURE 17. RR 12/U Window for use in both polarizations against frequencies above 8,000 mc.

For all frequencies above about 10,000 mc small squares of paper-backed foil (Figure 17) constitute a fairly satisfactory form of confusion reflector. The weight per unit runs high, around the two-lb level, but a single bundle covers the entire higher-frequency spectrum up through the heat region and into the visual. The bulk is not unusually great. The squares are cut by guillotine. The response is essentially independent of polarization.

12.2.9 Other Considerations regarding Window Operations

The foregoing discussion on the theory and application of reflectors to radar deception and confusion is by no means complete. For example, no mention has been made of the use of this type of material in mortar shells or rockets for front-line identification purposes. No dis-

cussion has been given of the development of methods for identification of Window echoes as differentiated from actual target echoes. No discussion of automatic dispensing is included, which, although a purely mechanical problem, affects the usefulness of this material very greatly. Finally, the operational phases of the problem have been touched upon only briefly. All these matters are discussed in some detail in a special report summarizing the work which has been done in this field,[734] which in turn refers to the original reports on the various phases of the activity. The above discussion, then, is designed only to give the reader an orientation in the field and to indicate its scope.

12.2.10 A Study of Persistent Echoes from Shell Bursts

Work was undertaken rather early with the object of discovering, and, if possible, controlling the mechanism or reflection associated with the persistent radar echoes from shell bursts. Preliminary measurements were made on conductivities of burning gases and of gases in contact with burning matter and on the effects of such gases on propagation in wave guides. These experiments showed that the conductivities involved were generally so low that no strong reflections of radar signals from the hot gases in an explosion should be expected. Actual shell bursts were then observed at the Aberdeen Proving Ground with a tracking radar. The echoes were found definitely to be due to the falling shell fragments and not to the hot gases, which do not fall but expand rapidly and in this case were quickly blown to one side by the wind. Confirmatory experiments were performed in collaboration with the Radiation Laboratory on radar echoes from quantities of nails dropped from aircraft. It was concluded that echoes from the hot gases in shell bursts would not be strong enough to be of any use in confusing enemy radars. In the preliminary experiments, striking effects were observed with burning phosphorus and experiments on phosphorus-loaded shells were proposed. These experiments were never carried out because the advent of Window yielded a simpler and satisfactory solution of the problem.

12.3 ELECTRICAL CONFUSION AND DECEPTION METHODS

Electrical confusion and deception devices offer interesting possibilities for countermeasures applications. The possibility of transmitting false signals on the enemy frequency occupied an appreciable fraction of the research and developmental time of Division 15, and, although none of the devices was carried past the simulated operational stage, they were ready and might have been used under somewhat different tactical situations.

Actually, three main lines of investigation were carried out in the electrical deception and confusion field. One of these, involving transmission of deception signals for early-warning [EW] radar, was actually used operationally with considerable success by the British. Service laboratories in this country did some work on these so-called Moonshine methods, and interesting results were obtained, but it is beyond the scope of this volume to describe such activities. Another type of electrical deception and confusion device upon which Division 15 did considerable work was the so-called Peter system, which (unlike Moonshine) was intended to confuse the direction, but not the range, of the target carrying the equipment. Finally, some attention was given to the various possibilities presented by the use of ordinary jamming transmitters in conducting electrical deception operations, and by the use of other manipulating means for deceiving and confusing enemy radar.

12.3.1 Electrical Pulse Repeater (Peter)

The basic element of the Peter system[148] is an r-f repeater unit located on a ship or aircraft which is a target for enemy radar. This unit picks up the enemy radar signal, amplifies it, superposes modulation (if desired), and reradiates the signal in the direction of the enemy radar. Unlike Moonshine, Peter reradiates only

SECRET

a single signal for each signal picked up and so causes no error in range indication.

The Peter unit makes possible at least three different procedures for confusing the enemy radar.

1. If the enemy radar is a tracking set using conical scan or lobe switching, the reradiated signal can be modulated by a periodic function synchronized with, and phased with respect to, the radar lobing rate. This will have the effect of producing a fixed error in direction to the enemy radar. The error can be as great as about 40 per cent of the total radar beamwidth. This technique has the additional advantage

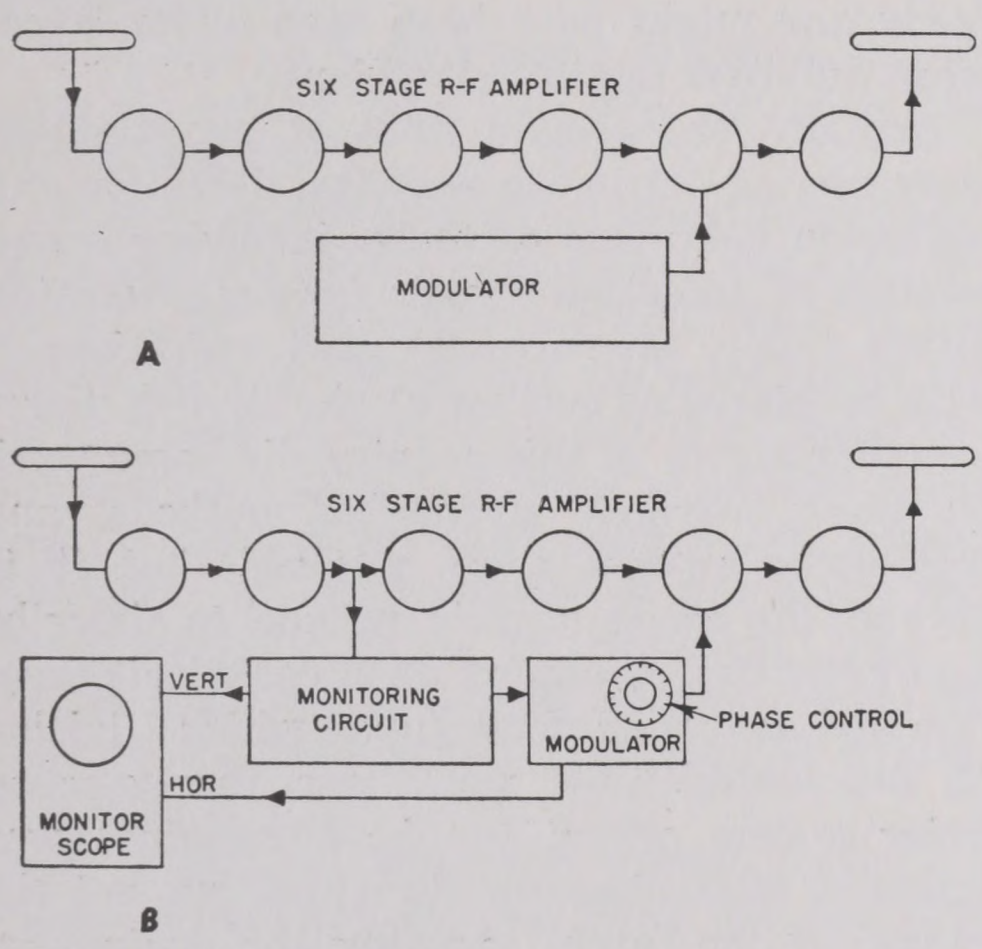


FIGURE 18. Type E and Type F of Peter systems.

that the radar operator will not be aware that the operation of this set is not normal. The final system of this type is referred to as the Type E Peter system.

2. A second type of Peter system, known as Type F, also effective against conical scan or lobe-switched tracking radars, modulates the reradiated signal with a random wave containing components uniformly distributed in a narrow band bracketing the radar lobing rate. This system avoids the necessity for monitoring and synchronizing with the incoming signal. The effect produced is no longer a fixed deflection of the radar but a random fluctuation of the apparent bearing which results in a "zone of uncertainty" which will amount to about 25 per cent of the total radar beamwidth.

3. The Peter amplifier can be used against any radar to increase the strength of the signal returned to the radar and so to increase the apparent reflecting area of the vessel bearing the Peter system. Thus a small boat can be made to look to a radar like a destroyer or a light cruiser. A similar procedure can be employed against radio-operated proximity fuzes, which detonate when a reflected signal from a target reaches a predetermined strength. Use of the Peter amplifier on the target will detonate the fuze when the projectile is still a safe distance away.

The greater part of the Peter development has been in the 500- to 700-mc range. The most satisfactory amplifier for this range is the parallel-plane (lighthouse-type) triode using a grounded grid circuit in a coaxial tuner.[131, 601] The amplifiers tested have usually included four to six such stages. When modulation is introduced it is applied to the penultimate stage. Block diagrams of Type E and Type F Peter systems are presented in Figure 18.

During operation it would be troublesome to tune the amplifier to the frequency of an enemy radar. Also it would be desirable to use a system capable of operating against several radars at once. Hence, a considerable amount of effort has been devoted to making the Peter system cover a very wide frequency band. Single-channel amplifiers having bandwidths of about 25 mc and voltage gains of 3 per stage have been built using L-14 tubes.

To achieve an extremely wide band, Peter amplifiers, each covering a fairly wide band, have been paralleled to form a multichannel receiver. The problem of the choice in multichannel amplifiers of the channel bandwidth and stage gain which will involve the smallest total number of stages to cover a given frequency band has been studied. The important conclusion emerges that the optimum stage gain is approximately 1.65, a conclusion which has served as a guide in the design of multichannel Peter systems. With standard GL-446 lighthouse tubes, channel bandwidths of the order of 20 mc are consistent with this choice

of stage gain. With the L-14 tube, bandwidths of over 100 mc should be obtainable.

It was feared initially that trouble might be experienced because of coupling between receiving and transmitting antennas. With reasonable antenna separations and orientations, no such difficulty has been encountered. With the two antennas mounted 25 ft apart with their axes parallel, the direct antenna-to-antenna signal is attenuated by more than 75 db at 550 mc.

The time delay in the Peter amplifier is of the order of 0.2 μsec, with the result that the return signal is actually superposed on the normal echo received at the enemy radar.

Several novel modulation procedures have been evolved to avoid the necessity for manual monitoring of the received signals and to provide accurate repetition of the received radar signal. A repeating modulator particularly for use in the Type E system against lobe-switched radars like the FD has been developed. In this modulator a perfect integration of the incoming signal is achieved without phase shift or time delay. The modulator for the Type F Peter system presented a difficult problem which was solved by playing back photoelectrically a sound track on which a sine wave whose frequency varied from 22.5 to 27.5 c had been recorded 100 times with random initial phase. This playback yielded a signal which approached noise very closely and which included only the desired frequency components.

An experimental Peter system has been built for operation at 3,000 mc. Satisfactory performance was achieved in a three-stage amplifier using L-14 tubes.

A system operating on the Peter principle has been constructed for operation in a 20-mc band around 125 mc for use against proximity fuzes. In this set the signal is heterodyned to a video frequency, amplified, and reconverted to the original frequency in a high-level converter.

The Peter system has had the following field tests:

1. A Type E Peter set mounted on a 75-ft launch and used against an aircraft homing with an ASB radar[125] caused the aircraft to miss on homing runs by 800 to 2,500 ft.

2. A Type E Peter set flown against an FD radar[126] caused tracking errors of 4 to 6 degrees compared with normal tracking errors of 1 degree.

3. A Type E Peter used against a synthetic Giant Wurzburg produced an error of 1.6 degrees.

4. A Type F Peter used against a synthetic Giant Wurzburg produced a zone of confusion of 1.0 degree.

5. A Peter system used as a straight r-f repeater against a Small Wurzburg and an RAF Type 11 search set gave an intensified echo equivalent to that of a destroyer.

6. The 125-mc Peter system has been tested against proximity fuzes at the Airborne Instruments Laboratory with satisfactory results.

12.3.2 Other Electrical Radar Deception Devices

Ordinary jammers may be used in conducting electrical deception operations. An amount of care in planning such a movement equal to that shown in planning the use of jammers to cover the real attack must be shown or the deception will not succeed.

If a bona fide raid is going to have certain radar countermeasures protection provided by Window and jammers, then it is possible to create a diversionary raid by using a small number of airplanes employing the same Window and jammers in such a way as to create an indication on the enemy's radar defense system which will duplicate that of the genuine raid.

The prime requirement in carrying out any deception is that no element of the system being deceived shall be able to see through the deception. Thus, countermeasures must be successfully applied to all the elements of an enemy radar system and other methods of detection by the deception flight if it is to succeed.

A possible deception technique that should be borne in mind is the use of pulse transmitters operating in the radar frequency bands. To a search receiver these transmitters would appear to be radar systems. It would be impossible to determine with certainty which

SECRET

emissions are actually from radars and should be jammed. Hence, if this method were practiced on a large scale, by measures against all the transmissions, a considerable amount of RCM equipment would be required.

A disadvantage that might result from the inauguration of this type of deception is the possibility that it will stimulate the acquisition and use by the enemy of jamming equipment for a large portion of the radar band of frequencies. Under such circumstances the frequencies that would be available for new radar equipment would be severely limited since the enemy would be prepared to jam over a good deal of the spectrum.

A subterfuge that may be practiced and is almost certain to cause both confusion and deception until detected is the operation of radar equipment on the same frequency as that of the enemy but with slightly different pulse-repetition frequencies. This would be almost perfect insurance against jamming unless the enemy were also willing to forego the use of his equipment operating on the same frequency. By the same token, operation on enemy radar frequencies is feasible only if it is more important to use our own radar than to deny the enemy the use of his by jamming.

On the other hand, one should always be alert to the possibility that the enemy may set up a radar system operating in the same frequencies as our own equipment. In a theater where a number of radar sets are in use it is common to experience interference from the other units. Since these emissions are not generally synchronized with one another, any given radar can successfully concentrate on its own signals and ignore those of other radars as they pass across the screen. It is well to ascertain, periodically, that all such interfering signals originate from one's own radar equipment.

SECRET

Chapter 13

RADAR ANTIJAMMING STUDIES AND TRAINING

13.1 INTRODUCTION

THE OVERALL purpose of the radar antijamming [AJ] program was to improve the performance of friendly radar systems in the presence of enemy offensive countermeasures. The program, therefore, included AJ training of operators as well as laboratory and field studies.

Because this program was concerned not only with jamming and AJ modifications to radars but also with fundamentals of radar design and operation, AJ research and development work was done under the auspices of Division 14 as well as Division 15. The latter phase of the program was carried out chiefly by the Radio Research Laboratory [RRL] of Harvard University (under contract OEMsr-411); the Division 14 work was performed mainly at the Radiation Laboratory [RL] of the Massachusetts Institute of Technology. In addition, several Service laboratories did AJ research. The large number of groups interested in the AJ program necessitated good liaison, which was successfully accomplished; especially close contact was maintained between Radio Research Laboratory and Radiation Laboratory.

Although this chapter deals primarily with the Division 15 aspects of the radar AJ program, the relationship of this work to that of the other groups is considered to some extent also. Moreover, much of the AJ research in nonradar fields, especially in communications, is applicable at least in part to radar AJ also, and vice versa; this is particularly true, of course, of the more fundamental phases. The AJ work in communications and other nonradar fields is discussed in Chapter 9 of this report. The theoretical aspects of AJ are considered in Chapter 6.

Much of the AJ program was in the nature of insurance. The offensive jamming of the enemy in general was not very extensive or effective, but it was necessary to be prepared for serious enemy counteraction. Such insurance measures included both retroactive modifications designed to improve the performance of existing radars and improved AJ design features for new sets.

The radar AJ effort of Division 15 is discussed below under the following headings: (1) Laboratory studies, consulting, and committee activities concerned with the development and application of good basic AJ design for radars. (2) Fundamental AJ studies, including research on basic AJ techniques and circuits, and basic laboratory studies on the relative effectiveness of various jamming signals. (The latter especially have yielded information of importance to the offensive countermeasures program as well as to the AJ effort.) (3) Investigations of specific radar equipments, including both studies of the jamming susceptibilities of U. S. radars and navigation systems, and the engineering of retroactive AJ modifications for radars already in the field. (4) The AJ training programs and the training apparatus used in them.

Many phases of the radar AJ work are summarized below. From the start, however, emphasis should be given to the most important conclusion reached: that good basic design and good operator training are the most important AJ measures for the protection of radars.

13.2 AJ DESIGN OF RADARS

During the course of the work on jamming susceptibility and basic AJ techniques (described below), it became apparent that the use of special tricks and "black boxes" as attachments to radar was in general much less effective against jamming than the application of sound engineering principles to the design of the radar. This conclusion is borne out by the fact that nearly all of the retroactive AJ modifications developed serve mainly to correct faults in the original design of the equipment, although it is true that several specialized circuits have proved useful against special types of jamming encountered operationally.

Therefore, one of the prime objectives of the AJ program was to facilitate the incorporation of sound AJ engineering principles into the design of radar equipments. Since Division 15 was not itself a radar development agency, this function was accomplished by helping to make available to such agencies all possible data on AJ engineering practices and by campaigning actively for the inclusion of these practices in radar specifications and designs. The methods of furthering these aims can be described in two main categories:

1. Representation on Office of Scientific Research and Development [OSRD] and Service AJ committees.
2. Consulting services furnished to radar designers and manufacturers and to the Armed Services.

13.2.1 AJ Committee Activity

By early 1943, the laboratory work on radar vulnerability and basic AJ techniques had reached the stage where it was most desirable that the AJ information be made available to the designers and manufacturers of radar equipments, since security regulations had until then prevented the dissemination of these data to agencies other than OSRD and Service laboratories. Accordingly, under the sponsorship of Division 15, an AJ Committee was formed in March 1943. Radio Research Laboratory was represented on this committee by several members of the AJ Division of the laboratory; other members represented Division 14 of the National Defense Research Committee, the War and Navy Departments, Army and Navy Service laboratories, and each major manufacturer of radar equipment. The function of the AJ Committee was to facilitate the interchange of AJ information among laboratories and manufacturers and to consider how the information could best be integrated into radar design. The initial activity was primarily technical, and over a period of several months papers were presented on the details and performance of a number of AJ circuits and on principles of good engineering practice. A few months after the committee commenced its activities, a survey was initiated among the manufacturers of radar equipment to determine to what extent AJ features and engineering were being included in new radar designs. The incomplete results of this survey led to the recognition of the great need for a compilation of the basic principles of good AJ practice, to be used by radar designers and manufacturers and by the Service personnel engaged in formulating military characteristics and specifications for radar equipments; for it was realized that AJ features would not be included in radar designs unless the specifications required it and unless the designers had the AJ information available.

This compilation of basic AJ design features was undertaken by the AJ Practices Panel, consisting of representatives from Radio Research Laboratory, Radiation Laboratory, Service laboratories, and the Army. A thorough survey was made of the field to be covered, which showed that considerably more laboratory work was necessary to present a complete summary of good AJ engineering practices. The work was allocated among the various research laboratories represented, and papers were written on their respective results.

The Division 15 AJ Committee, not being a Service organization, could go no further than to recommend that AJ features be included in radar equipments. This fact was recognized by the Service members of the committee, and in early 1945 the AJ Working Subcommittee of the Joint Countermeasures Committee was formed, with an RRL member included. This committee attacked the problem of using official channels to obtain the incorporation of AJ engineering in radar design. It recommended that satisfactory AJ performance be specified as a military characteristic and that the inclusion of AJ engineering in radar gear be the responsibility of the radar design agency as an integral part of development and production specifications. The committee prepared a comprehensive catalog of AJ devices and techniques.

It is to be hoped that the work of these committees and panels will enable future electronic equipment utilizing space radiation to

be designed with the principles of sound AJ engineering in mind.

13.2.2 AJ Consulting Activity

To supplement the committee activities, consulting service was supplied to the Army and Navy on various occasions. This took the form of advising the Service laboratories or manufacturers regarding the inclusion of AJ engineering in new equipment designs, of assisting the Armed Services in formulating specifications for radar equipments to include AJ requirements, and of assisting in the preparation of AJ training publications and films (see Section 13.5).

On a number of occasions, AJ representatives were requested to sit in on early design conferences for new radar equipments. The basic principles of good AJ engineering were explained for the guidance of the design engineers in avoiding some of the obvious faults which render radar particularly susceptible to jamming, and the AJ aspects of the particular system were considered in detail. Some of the equipments on which such consulting service was rendered are the AN/APG-3, AN/APG-16, AN/APS-19, AN/TPL-1, and Mark XII radar.

Early in the design of the AN/APS-19, recommendations were requested for any design changes which would improve the AJ characteristics of the final model. Several measures were proposed. These included the provision of a manual gain control to permit homing on jamming, removal of the i-f gate, addition of a short time-constant video coupling, and widening the video bandwidth. Also, the designers of the equipment were given information on methods used to determine the performance of the AJ features. No data are available to show the efficacy of the measures recommended.

The U. S. Navy requested the AJ Practices Panel to recommend changes in the design of the Mark XII fire-control radar which would reduce its vulnerability to jamming. After a study of the radar, a number of possible improvements in its AJ performance were suggested to the Navy. Here again, no final vulnerability studies are available to evaluate the usefulness of the AJ features.

The AN/TPL-1 radar (an S-band, antiaircraft fire-control equipment) was referred to the AJ Practices Panel for study while it was still in the prototype stage. In cooperation with the design engineers, a very close examination of the equipment was made and jamming tests were conducted on the prototype. As a result, a number of circuit changes were recommended from the AJ point of view. It was feasible to include most of the features suggested in the final design, and the production model was tested for jamming vulnerability (see Section 13.4.1). Compared to previous equipments without built-in AJ features, the TPL-1 suffers much less loss of operating efficiency; in addition, an AJ switch which throws in a short time-constant coupling circuit permits a definite improvement in performance under jamming conditions. It was considered, therefore, that the efforts expended on the AJ circuits of the TPL-1 were amply justified and that the results exemplify the benefits of sound AJ engineering.

13.3 FUNDAMENTAL AJ STUDIES

The first step in an AJ research program, of course, must be to determine what it is that permits a radar to be jammed. As found from theoretical calculations, from basic laboratory experiments, and from vulnerability studies of particular systems, the effectiveness of a jamming signal depends both on the characteristics of the radar and on the nature of the jamming. This result leads quite logically to two further steps: the study of the effects of various jamming signals upon different radar types, and the study of basic methods for improving radar system operation in the presence of jamming.

Such studies were made and are described in this section. In many cases, theoretical analyses were carried out in addition to the experimental investigations, either in advance or concurrently; these are discussed in detail in Chapter 6, and specific references to the proper sections thereof are given at the appro-

priate points below. Not only did the theoretical work help give direction to the experiments and indicate their goals, but if it was confirmed by the experiments it enabled their results to be generalized considerably. It should be noted that the results of these fundamental AJ investigations were useful not only in the protection of radars against jamming but also in the design of jamming transmitters and in the analysis of their capabilities.

The AJ program in the United States did not completely follow the logical pattern of basic research succeeded by developmental research and then specific engineering. As various agencies became engaged in the AJ problem, progress was made in all three phases at once: more exact understanding of jamming effects, more detailed understanding of radar and AJ circuit characteristics, and more enlightened engineering of application. The work was done somewhat in parallel among the various organizations, with informal individual liaison and joint-committee activities serving to maintain a nominal overall direction to the effort. Even within a particular organization, it was usual to find both basic research and specific engineering in progress simultaneously, often within the scope of a single project.

13.3.1 Basic AJ Techniques and Circuits

In the investigation of the AJ abilities of various radar systems and circuits, the problems to be solved are the specific determination of the characteristics contributing to jamming susceptibility and the development of refinements and changes in circuit design which yield improved characteristics. A good understanding of these matters is essential to the final technical step of engineering suitable AJ characteristics into specific radars.

Circuits and Methods

The projects directed to such basic AJ research were quite varied and can best be described on a more or less chronological basis.

High-Pass Filters. An early investigation of the design requirements for high-pass video filters was performed as an adjunct to a susceptibility study of the SCR-268. The possibilities of using such filters, suggested in a very early report,[497] were experimentally examined, and it was concluded that a simple RLC filter was the most satisfactory. The filter was found quite effective in reducing the confusion on a deflection-modulated scope resulting from jamming modulated at a low frequency.[792, 793] Further consideration was given to the high-pass filter in connection with its use in the Navy Mark IV (FD) radar; it was found at this time that a simple RC filter (with the RC product equal to the radar pulse length) was practical and valuable in removing modulation components of the jamming resulting from the lobe switching.

Back Bias. The matter of back bias also received considerable early attention, as a means for improving the overload limit level of a radar receiver. It was found that, on a steady-state basis, a back-biased i-f amplifier would withstand a jamming signal equal to its normal gain times the signal level which caused overload without back bias. Further, in a multistage amplifier, each stage should be individually and successively back-biased as its input jamming signal level increased. Amplifier-type back-biasing circuits were found to be able to equal the performance of manual biasing and to follow a medium frequency-modulation envelope as well. Cathode-degenerative biasing was found much less effective.

Gain Control. In the course of the back-bias work, comparisons were made between one type of manual i-f gain control and the back-biasing methods. It was found that the ultimate benefits of a gain control in the reduction of overload jamming effect were less than those of an optimum back-bias system. However, the availability of a gain control on current radar receivers and its simplicity as compared with the biasing schemes made it sufficiently important as an operational AJ measure to warrant an extensive comparison of grid, cathode, screen-grid, and plate-screen-grid controls. Concurrently, operational radar jamming tests indicated the usefulness of informed gain-control manipulation. The study brought out the importance of controlling gain at an early i-f stage and of controlling a sufficient number

of stages to achieve the necessary overall range.

Oscillator Detuning. A similar study was made to establish the limits of another operational AJ feature: local oscillator detuning. In general, it was found that local oscillator detuning functioned in the manner of gain control to prevent overload, with the added advantage of discriminating more effectively against slightly off-tune jamming.

Integration. By and large, the early AJ projects were concerned with remedies for the simpler types of jamming. Basic studies had early shown the difficulty of countering complex jamming such as pure or direct-noise amplifier (Dina) noise. A research program was instituted on the possibilities of integrating (or averaging) a noise jamming pattern on an oscilloscope, either photographically or otherwise, in order to favor a steady repetitive pulse over the random noise. Tests coordinated with theoretical studies (see Section 6.2.2) indicated a practical limit of 6-db gain (over direct viewing) through using time integration of a deflection-modulated scope by photography or long-persistent cathode-ray screen methods.[73, 379, 575, 583] It was felt that there were no practical applications for this method as an AJ measure in the existing war program.

Errors from Lobe Switching. The practical problems of fire-control radar emphasized the importance of maintaining linearity in the receiving system of a lobe-switched radar to prevent directional errors from differential jamming overload between the lobes. Several ideas for reducing such errors were investigated, including methods to increase the dynamic range and linearity of the second detector. A comparison between square-law and diode detectors was made[681] in connection with a specific engineering AJ application to the SCR-268. An experimental study was made of the idea of lobe switching only the transmission of the radar, with reception on a single fixed receiving antenna; the results, as expected, showed that errors caused by off-target jamming were eliminated.[610]

Anti-Window Devices. Methods for tracking targets through ground clutter, sea clutter, clouds, and Window received attention from practically all radar and radio countermeasures [RCM] laboratories in the United States. The possibilities of the high-pass video filter against clutter on air-to-surface vessel [ASV] radar were noted in field tests.[597] An early field test of the detection of propeller modulation as a means of differentiating between aircraft and decoy echoes[372] preceded an extensive research program on the Sambo project at Radiation Laboratory and Naval Research Laboratory; this was followed at a later date by a project in which the usefulness against clutter of an aural detector for propeller modulation and doppler beats was demonstrated.[673] Another approach to the anticlutter problem was the extension of the dynamic range for signals presentable on an intensity-modulated indicator. Several "gain-compressing" video circuits were devised, the most promising one using crystals as nonlinear circuit elements.[767] Consideration was given to the use of a very short time-constant coupling in the video as a differentiator; a theoretical analysis (see Section 6.3.1) showed that if this device were combined with an increased receiver bandwidth it would be equivalent to shortening the radar pulse length.

The differentiation of real naval targets from decoys or spoofs was solved with a radar modification which made it practical to observe the multireflection detail of a ship as compared with the simple, single-surface reflection of a spoof. It was found that observation of the behavior of an echo as a slight frequency modulation was applied to the radar transmitter signal, or simply study of the echo with a high-definition receiving system and expanded-sweep scope, permitted a reliable interpretation of a given echo[690] (see Section 6.3.1).

Miscellaneous Devices. Several devices and circuits proposed or used by other AJ groups were examined in the course of the Division 15 program, including a study of a pulse-amplitude discriminating system (George Box) and an operational check of the German look-through device known as Stendal B or Goldammer, which operated by selecting the proper polarization. Reports were not issued on this work.

In addition, several original ideas for AJ measures were studied at RRL. The use of

[redacted]

lobing for transmission only was noted above. A method for the cancellation of separately induced cross-polarized components of a circularly polarized jamming signal was shown to be practical in both laboratory and field tests. This work aroused Service interest from the offensive as well as defensive RCM point of view, because of the widespread Allied use of circularly polarized jamming.[705] As a further outgrowth of this project, a jamming cancellation system was applied as a look-through aid to a setting-on receiver in a spot-jamming system and successfully flight-tested.[670] The idea was incorporated in the last jammer system development, Elephant (see Chapter 11).

Summary and Conclusions

The foregoing would indicate that the basic research program of Division 15 in the AJ field was somewhat disconnected. To a certain extent, this activity was fitted into a more complete overall pattern, involving all laboratories engaging in AJ work; in retrospect, however, it is apparent that this overall effort might have been more closely coordinated. On the other hand, the study, research, and field tests performed by United States agencies led eventually to a reasonably definite body of AJ philosophy based on fact which can be summarized as follows:

1. High-power high-definition radar systems have been proved in practice to be superior in AJ operations.

2. Tunable radars which have been developed for both low frequencies and microwaves in the form of experimental models have proved the value of a single-dial tunable radar as an AJ system. There is factual evidence that tunability is foremost as an AJ measure. Frequency spread of radars, which serves the same function, is a corollary and equally important.

3. Practical incorporation of dynamic ranges in receivers sufficient to handle inputs of hundreds of millivolts has been demonstrated, with methods running from clean high-power i-f amplifier design to clever trick-feedback circuits and automatic biasing arrangements. Many practical circuits have been evolved especially to handle strong clutter signals.

4. The useful limits of video filtering and the proper design features of video filters have been shown both for antijamming and for anticlutter work.

5. The advantages of clean design and of circuit stability as aids to AJ performance have been demonstrated.

6. The requirements for signal presentation have been well established, including the AJ advantages of deflection modulation and sharp focus, and, in a few cases, of persistent phosphors.

7. The relation of video and i-f bandwidths to each other and to the radar signal spectrum have been established. The optimum i-f bandwidth is equal to 1.3/pulse time duration, and the video must be equal to or greater than the total i-f width.

8. The importance of linearity in fire-direction radar receiver circuits has been shown and an indication found of how it may be achieved.

9. The value and necessity of moving-target indication schemes have been proved, but demonstration of the extreme vulnerability to electronic jamming inherent in such systems has led to the problem of combining tunability with moving-target detection.

10. Pulse width and amplitude selecting schemes have been shown to have value in limited circumstances, especially where they serve to alleviate operator fatigue.

Special AJ measures and circuit tricks, because of their limited scope, are not recommended for general radar application. Radar design should be strengthened along lines of tunability, stability, good shielding, wide dynamic range, linearity, higher power, optimum definition, ease of operation and interpretation, and freedom from clutter interference. "Doctoring" for special cases of jamming should be incorporated only when such a special case exists, to eliminate much normally useless circuitry. However, the limits and capabilities of representative special AJ circuits must be known in case their emergency use is required. The manufacturer should provide basic AJ design, and the Armed Services should have trained specialists on hand to doctor, point out operating tricks, and educate the operators in AJ continually.

SECRET

13.3.2 Basic Studies of Jamming Signal Effectiveness

During 1943 and the early part of 1944, a series of laboratory studies[551, 563, 569, 573, 578, 584] were carried out under carefully controlled conditions to determine the relative effectiveness of various types of jamming signals against both deflection-modulated and intensity-modulated indicators. The primary purpose of these studies was to determine the most efficient type or types of jamming for use in offensive countermeasures; in the course of the work, however, information of interest from the AJ point of view was also obtained. The results are summarized here, first from the point of view of offensive countermeasures and then from the AJ point of view. Theoretical analyses of some phases of the work are discussed in Section 6.2, and the results of similar studies on communications systems are described in Chapter 9 and also in Section 8.2.2.

The efficiency of the various types of jamming signals was measured in terms of the *jam-to-signal* [J/S] ratio—the ratio of the jamming power to the signal power—in such a way that the radar pip is detectable just 50 per cent of the time. In the studies of both amplitude- and frequency-modulated jamming, J/S is the ratio of the rms unmodulated carrier power of the jamming to the rms of the radar output multiplied by the inverse of the duty cycle (the so-called "peak power" of the pulse). In the case of pure Dina noise, J/S is the ratio of the rms of the noise to the "peak power" of the pulse. For pulse jamming, two types of ratios were used. The ratio of the peak power of the jammer pulse to the peak power of the radar pulse is $J(\text{peak})/S$. The ratio of the rms of the jammer output to the peak power of the radar pulse is $J(\text{rms})/S$.

All of the types of jamming studied may be classified as either periodic or random. Periodic jamming includes sine-wave amplitude modulation, sine wave frequency modulation, and periodic pulse jamming; and random jamming includes noise amplitude modulation, noise frequency modulation, Dina, noise (no carrier), and random-pulse jamming.

Results from the Offensive RCM Aspect

All types of periodic jamming are completely ineffective in the absence of overloading, against any system which employs a deflection-modulated scope.

All types of random jamming are effective against deflection-modulated scopes. The degree of effectiveness, however, varies among the several types and also in a function of the several parameters of each particular type.

With noise amplitude modulation, an increase in percentage of modulation increases the effectiveness of the jamming by an amount equal to the resulting additional power in the sidebands. The variation in the effectiveness of the jamming as a function of the degree of clipping of the modulating noise is dependent on the bandwidth of such noise. If the bandwidth of the noise is not greater than that of the receiver, varying the peak factor from 5 to 1.5 does not greatly change the effectiveness of the jamming. If, however, the bandwidth of the noise is of the order of ten times the bandwidth of the receiver, then greater clipping results in an increase in effectiveness equal to the resulting increase in the power of the sidebands.

The importance of the dependence of the effect of clipping upon the bandwidth of the noise should be emphasized. For example, with a noise a-m jammer which has a bandwidth of the order of ten times the receiver bandwidth and which employs highly clipped noise for modulation, one can not only jam the channel to which the jammer is tuned more effectively than with a jammer of equal total sideband power which has a bandwidth equal to that of the channel, but one can also jam almost as effectively almost all the other channels covered by the wide-band jammer. The fact that ten times as much energy is accepted by the receiver when the narrow-band jammer is employed is offset by the fact that the narrow-band clipped noise appears clipped on the scope of the receiver and hence is a much less efficient jamming signal.

With noise frequency modulation an increase in clipping, as a general rule, results in more effective jamming. In addition, the larger the frequency deviation, the greater is the jamming

SECRET

effectiveness (within the limits studied). If the bandwidth of the noise used for frequency modulation is too narrow or too wide, the jamming is less uniform than if the optimum bandwidth is used. The optimum bandwidth depends upon the frequency deviation, the noise peak factor, the bandwidth of the modulating noise, and the receiver bandwidth.

Sine-wave frequency modulation plus noise amplitude modulation is an effective jamming signal. The best case of such jamming is about as effective over the barrage width as the best case of jamming by noise frequency modulation. Adding sine-wave frequency modulation with a frequency deviation of the order of the receiver bandwidth to narrow-band noise amplitude modulation makes the noise appear random on the scope of the receiver and increases the effectiveness of the jamming by about 7 db. Sine-wave frequency modulation plus noise frequency modulation is inferior as jamming both to sine-wave frequency modulation plus noise amplitude modulation and to noise frequency modulation.

If noise frequency modulation plus noise amplitude modulation is produced by one noise source, the energy spectra tend to be markedly asymmetrical and the effectiveness of the jamming varies greatly over the barrage width. Systematic relations exist between the f-m and a-m sidebands such that in some cases they tend to reinforce and some cases cancel each other. If independent noise sources are employed, symmetrical energy spectra are obtained. The best case of noise frequency modulation plus noise amplitude modulation, however, is no better than the best case of noise f-m jamming.

The higher the upper frequency limit of the noise used to trigger random-pulse jamming, the more such jamming looks like receiver noise and the more effective it is. In designing a random-pulse jammer, it makes little difference whether the primary consideration is peak power output or rms power output. In either case, the upper frequency limit of the triggering noise should be about five times the bandwidth of the receiver to be jammed and the pulse length should be of the order of 1/15 $\times$ receiver bandwidth. Under such conditions, the barrage width is about equal to 1/1.4 $\times$ pulse length.

Results from the AJ Point of View

Periodic jamming, although completely ineffective against a deflection-modulated scope in early-warning [EW] radar systems, is, generally speaking, effective against all systems which employ an intensity-modulated scope. Moreover, many types of random jamming are much more effective against an intensity- than against a deflection-modulated scope. These two facts make it appear highly desirable that auxiliary A scopes be provided for radar systems which normally employ intensity-modulated scopes and which are likely to encounter jamming of any kind.

The relation between the effectiveness of any given type of jamming and overloading of the receiver depends upon the characteristics of the particular receiver being jammed. Although the increase in some cases is negligible, both i-f and video overloading tend, in general, to increase the effectiveness of all types of jamming. It is important, therefore, that radar receivers be designed in such a manner that the possibility of overloading is minimized.

An analysis of the results obtained indicates that in many cases a variable receiver bandwidth would be a useful AJ measure. Thus, for example, as indicated above, increasing the frequency deviation increases the effectiveness of noise frequency modulation in jamming. The converse of this is that, if the frequency deviation of the jamming is held constant, then increasing the receiver bandwidth will decrease the effectiveness of the jamming. Similarly, if one is working through random-pulse jamming, doubling the receiver bandwidth may cause a marked decrease in the effectiveness of the jamming. Under certain circumstances with noise amplitude modulation and with Dina noise, a decrease in the receiver bandwidth results in a decrease in the effectiveness of the jamming.

13.4 STUDIES OF SPECIFIC EQUIPMENTS

After the fundamental principles of AJ had been investigated, the next step was to apply

SECRET

them. The methods used to ensure the incorporation of these principles in new radars has been discussed, but there remained the problem of the radars already in use which had been designed without regard for AJ considerations. This problem was attacked by studying the vulnerability of such equipments to jamming and then designing modifications, if possible, to render them less vulnerable.

13.4.1 Jamming Susceptibility of U. S. Radars

In order to improve the performance of a radar set in the presence of enemy jamming, it is necessary to know quantitatively how much its operation is impaired by Window and by the various types of electronic jamming signals which may be encountered. The problem of Window jamming susceptibility is considered in Chapter 12. The paragraphs below describe the numerous investigations on the susceptibility of radar sets to electronic jamming, as well as the one study that was made of the susceptibility of the long-range radio-navigation (Loran) system. In these studies, after the vulnerability of an equipment had been determined, a circuit analysis was generally carried out (in a varying degree of detail) to determine the reasons for the observed effects of the jamming, so that remedial measures could be recommended.

Results of Studies

In accepting susceptibility projects from the Armed Services, the policy was to make at least one prototype study of each type of radar equipment but not to undertake numerous studies of a given type. The various sets for which studies have been made are listed in Table 1, together with pertinent data and references. The arrangement is roughly chronological. The results of these studies are discussed in the paragraphs below. The AJ modifications listed are described in detail in the next section.

In general, it may be said that the United States radar equipments tested were rather susceptible to electronic jamming. This was particularly true of searchlight-control [SLC] and fire-control sets, such as SCR-268, Mark IV, and AN/APG-1, where high directional accuracy must be maintained if the set is to remain functional. SCR-545 and AN/TPL-1 showed better performance, particularly the latter, a new set with much better AJ design.

The ASV sets studied were affected by jamming to the point where a ship target could screen its range over all azimuths by means of a medium-power jamming transmitter. This was true even in the case of a recent set such as AN/APS-4.

The work on the radar homing bomb [RHB] and Mark XXXI sets deserves special mention. These are radar-controlled bombs that automatically home on a target, and they proved to be extremely susceptible to electronic jamming. Automatic tracking radars are inherently easier to jam than manually controlled sets, but the analysis of these sets led to several suggestions for improvement. The same was true of the AN/APG-1. The performance of the automatic tracking in SCR-545 was found to be much better. These studies led to detailed consideration by radar design groups of the autotrack problem.

Measurement Techniques

The results of the laboratory susceptibility studies were expressed in terms of J/S ratio (ratio of jamming power to peak-signal power). A direct calibration of these ratios was obtained by observing the beat resulting from simultaneous reception of pulse and continuous-wave [c-w] jamming. An absolute scale of jamming power was established by measurement of the field strength at the radar antenna, or, in the case of S-band studies, by use of a calibrated thermistor bridge.

For S-band studies, the Boonton Type L-102 variable-phase pulse generator was found to be very useful. A laboratory modification was worked out whereby these generators could be converted to c-w or modulated c-w operation and used as sources of test jamming signals. Both normal and converted L-102 units are equipped with calibrated output attenuators and built-in thermistor bridges.

In addition to laboratory susceptibility studies, tests were carried out on the jamming sus-

SECRET

ceptibility of several sets during actual field operations. Although this work was intended primarily as a check on the laboratory susceptibility studies, some of it was pioneer work in the field operation of jamming transmitters for spot jamming.[624]

For field susceptibility tests on S band, it was necessary to develop a jamming transmitter.[459] The result was a quickly built equipment rugged enough for field service, using a Type 410-R klystron. It was used on Lake Okeechobee, Florida, against the ASG and SCR-717B radars.[597] This transmitter was the forerunner of later S-band jamming transmitters, and the tests in which it was used served to demonstrate the practicality of spot jamming of S-band ASV radar systems.

A similar situation developed in 1945 when field susceptibility tests on the AN/APS-4 X-band ASV radar were contemplated. A field jammer for use in the tests was developed using experimental models of the RCA Type A-131 magnetron.[754] Because of the ending of World War II, the equipment was transferred to the Navy Bureau of Aeronautics, which proceeded with the actual field work.

Measurements of jamming susceptibility had a double function in the AJ program. In the first place, when combined with an estimate of the enemy's ability to produce jamming signals, they made possible an evaluation of the general defensive position of United States systems. It was on the basis of this evaluation that the military supported corrective measures either to meet an immediate need or as insurance. In the second place, the detailed analyses of circuits and operation that formed a part of most susceptibility studies were the technical basis for AJ modifications and for advice on new radar design and development.

TABLE 1. Radar susceptibility studies and AJ modifications.

Set No.	Type	Frequency	References*	AJ modifications	Modification† references
Loran	Navigational	1.95 mc	516	.....	.....
SCR-268	Land-based SLC	200 mc	520	E-1610, E-1601, E-1602, E-1602A, E-1606, E-1607	794, 620, 681
SCR-521A	ASV search	176 mc	532	.....	.....
Mark IV	Ship-borne fire-control	700 mc	549	E-510, E-515, E-2106	401, 406, 438, 469, 517
ASG	ASV Search	S band	537, 538, 597	.....	.....
SCR-717B	ASV Search and LAB	S band	570	L-901	542, 380
RHB	Guided missile	S band	633	.....	.....
Mark XXXI	Guided missile	S band	648	.....	.....
SCR-720A	AI and ASV	S band	684	.....	.....
ASB	ASV search	5.15 mc	680	E-410, E-412, E-413, E-409, E-411	680, 795
AN/APQ-5B	LAB attachment	Video	703	Field modification	.....
AN/APG-1	Airborne automatic GL	S band	712	Field modification	.....
AN/APS-4	ASV and LAB	X band	713	.....	.....
AN/APA-16	LAB attachment	Video	713	.....	.....
AN/TPL-1	Land-based SLC	S band	717	.....	.....
SCR-545	Duplex search and GL	200 mc S band	729	.....	.....

* Reports concerned with the susceptibility studies.
† Reports concerned with AJ modifications (see Section 13.4.2).

13.4.2 AJ Modifications for Existing Equipments

Soon after AJ research was begun, it was felt that an immediate need existed for giving AJ attention to several specific radars then

SECRET

widely used by the Armed Services. The first radar studied was the Navy Mark IV (FD), for which the application of several known AJ palliatives was considered. From a previous susceptibility study and from a field jamming trial several possibilities were indicated,[401] and experimental work was undertaken.

At various later dates, similar applications of AJ engineering were attempted for the SCR-268, SCR-717, and ASB radars. In all these cases the intention was to "clean up" any particularly bad features of receiver circuit design, and often to add simple attachments, such as switchable high-pass filters or detuning controls. It is difficult to set any value on this program, for there were no cases reported where any of these devices saw operation against jamming. Many of the units did reach the Armed Services, however, and for their insurance value and the experience gained in their development, the effort can be considered generally constructive. Table 1, in the preceding section, lists the more important devices completed, and they are described in the summary below.

Navy Mark IV (FD) Radar

A number of AJ devices were designed for this fire-control radar. These included the following.

Plug-in High-Pass Filter E-510. A simple RC video filter which could be switched in as needed, with an RC product approximately equal to the pulse length, was arranged for installation by placing an adapter plug under a video amplifier tube.[406] This device was procured as a field modification kit by the Navy.

Local Oscillator Detuning Attachment E-512. This modification, consisting of a small variable condenser to provide vernier tuning of the local oscillator, was not procured, but it was described in order to have the design information available should need arise.[469]

Very High-Pass Video Filter E-515. This device involved several additional tubes and in effect replaced the normal second detector and part of the video chain. It provided the AJ advantages of a more linear detector and of a choice of three very high-pass, sharp cutoff filters. It was based on the fact that a jamming carrier is usually sufficiently off tune to produce a medium- or high-frequency beat with the pulse signal. The filters could be chosen to select and amplify this beat signal, presenting it directly on the scope screen. Navy procurement put this attachment on most of the Navy Mark IV radars, and later the unit was adapted to the Army SCR-296 radar.[438]

Army SCR-717B Radar

A laboratory susceptibility study[570] and a series of flight tests[380, 542] led to the design of the *L-901 replacement video unit.* This device mechanically and electrically replaced the usual SCR-717B video to provide improved video bandwidth, increased dynamic range, and a switchable high-pass filter. Limited procurement resulted in the installation of a few units in operational radars. Although the nature of the modification was such as to improve the AJ characteristics of the radar, the greatest operational interest was in its action against sea clutter.

Army SCR-268 Radar

The SCR-268 received early attention in the first radar vulnerability study[520] and was the vehicle for early high-pass filter studies. Early in 1944, a somewhat more extensive program of specific AJ modifications was undertaken.

Plug-in High-Pass Filter E-1610. The first project resulted in the mechanical adaptation of a plug-in high-pass video filter using a single switchable RC section. This unit was produced in limited quantity for shipment to the stricken SCR-268's at Anzio in the Mediterranean Theater of Operations. However, it arrived slightly later than a superior AJ device, a 3,000-mc replacement radar for the 268's.[794]

Replacement Detector and Video Units E-1601/1602. These two devices were designed to work together with certain circuit changes to provide the following advantages: increased video dynamic range, increased video-frequency bandwidth, increased linearity (detector and video), availability of switchable high-pass filters, and increased gain-control range. The two units were arranged to replace the detector and video stages. The E-1601 came in the form of fabricated adapter plugs which were inserted in the second detector and first video sockets

in the 268 receiver unit, while the E-1602 was a fabricated box which mounted over the sockets normally occupied by the final video stage and was connected into the circuit by means of a plug adapter. The gain-control range extension was achieved by applying the control to an additional i-f stage.[620, 681]

Limited procurement enabled some of the modification kits to be shipped to the few remaining operational SCR-268 radars. Improved models of the video unit (E-1602A) used a simplified circuit; E-1606 provided low-pass filters as well as high-pass. These units were not procured.

Navy ASB Radar

An attempt was made to dovetail specific "gadget" engineering with laboratory susceptibility and field test studies. A series of jamming flight tests was followed by a laboratory susceptibility study, which led to the preliminary design of several AJ modification devices. A second flight test program served to indicate the operational feasibility of these modifications.

Plug-in High-Pass Filter E-410. Similar to those for the 268 and Mark IV radars, this filter provided for remote control by the radar operator and also a rearrangement of the circuit connections to apply one section of the detector duodiode as a fast-recovery diode on the RC filter. A limited number of these units were procured and distributed by RRL.

Transmitter Remote-Tuning Attachments E-409 and E-413. A simple mechanical drive unit was arranged to provide the radar operator a chance to tune the transmitter as well as the receiver, making a completely tunable radar. Actual flights against a carefully monitored spot jammer revealed that the radar operator using a tunable system had a definite advantage over the jammer and could usually make what would have been successful torpedo-approach runs.

Gang Tuning Attachment E-411. This was a gear-box unit which enabled ganged drive of the normal receiver tuning and the added transmitter tuning units. The unit simplified system detuning and, through a disengaging gear arrangement, allowed separate receiver tuning. With the E-409 and E-413 units, the device was developed to the prototype stage and turned over to the Navy Bureau of Aeronautics for consideration. Rapid replacement of the ASB radars reduced the potential value of these units.[680, 795]

The actual contribution of the gadget-designing program to the AJ effort was not important. To a limited extent, however, the program served to indicate the possibilities and limitations of field modifications should real AJ needs arise, and above all to emphasize the importance of tackling the basic AJ problems from the point of view of radar design.

13.5 AJ TRAINING ACTIVITIES

The importance of operator training as an AJ measure was brought out forcefully by experiences in making susceptibility studies and in operating a variety of radar systems in the field. A great deal can be done to reduce or nullify the effectiveness of jamming by proper manipulation of receiver and oscilloscope controls. For instance, in the case of a search set that overloads easily, proper adjustment of the manual gain control can improve the performance a thousandfold or more. Careful training of operators in the use of these controls is absolutely necessary, if the improved performance is to be realized. Operator training also results in a greatly increased ability to read through jamming patterns which confuse but do not completely obliterate the target indications on the cathode-ray oscilloscope. Another purpose of training is to ensure that operators continue to operate their radar when jammed, rather than shut down on the supposition that the set is defective. In this way much useful information may be obtained that might otherwise be lost because of panic.

The AJ training activities in Division 15 may be divided into four parts: lectures on AJ to groups of Army and Navy officers coming to RRL for RCM training, a complete AJ training course for Navy officer-instructors, development of transmitters and signal generators for use in AJ training, and activities in connection with training films.

13.5.1 Officer Training Courses

During the first 2 years or so of RCM activity, the United States RCM program was in the development stage. Toward the end of this period some equipment was in production and small quantities were available to the Armed Services. Training of personnel in the use of this equipment became an important problem. Since RRL was the seat of a great deal of the development, it was appropriate that it should assume the responsibility of training selected groups of officers. The training took the form of a series of lectures on the various phases of RCM equipment and techniques, repeated at suitable intervals. Lectures on AJ were included in these series and covered both AJ equipment and operational methods. Seven Navy courses and nine Army courses lasting one to two weeks each were given, with an average attendance of about thirty.

The AJ training course for Navy officers was initiated at the request of the Bureau of Personnel as part of an overall plan for providing AJ training in the various schools operated by that bureau. Twelve officers representing the schools attended a one-week course of lectures and laboratory work at RRL in Cambridge and a two-week course of lectures and operational practice at the Naval Training School, Fort Lauderdale, Florida. Two officers from this first group then took over the job of training succeeding groups of officer-instructors. A sizable syllabus of reference and study material was prepared at RRL and distributed to the officers attending the RRL part of the course. This syllabus contained a laboratory manual for the four laboratory experiments,[476] a condensed summary of information on AJ techniques and devices, and numerous reprints of pertinent technical articles and reports.[593] For the operational part of the instruction at Fort Lauderdale, considerable RCM equipment was installed on an 82-ft Coast Guard patrol boat and operated against shore-based radar systems. This installation continued to be used by the Fort Lauderdale and Hollywood Beach training schools after the instructor training program was completed.

TABLE 2. AJ training equipment.

No.	Type	RRL Project No.	Frequency	Power output	References	Remarks
AN/UPT-1	Practice jammer	F-2800	450-720 mc	8-4 w	802, 803, 456	Modified AN/APT-2.
.....	Practice jammer	F-2000	450-720 mc	8-4 w	456	Modulations differ from those of AN/UPT-1.
AN/UPT-T4	Practice jammer	F-3800	175-550 mc	7-30 w	456, 798,	Modified AN/APQ-2.
RF-9/UPT	Oscillator	F-4100	100 kc, 400 kc 2-power frequency	Low	456, 797 799	Modulator for AN/APT-2, AN/APT-3, or AN/APQ-2.
.....	Jamming signal generator	A-1700	2,400-3,700 mc	6 mw	347, 796	6-ft relay rack.
TPQ-T2	AJ training set	P-525A	90-270 mc	½ w	800, 801	Wide selection of modulations.
TS-109/SPA	AJ training attachment	E-1300	.....	Low	480	For Navy Mark I, FD trainer.
.....	Switching unit	E-2000	.....	....	476	For use with SC radar.
.....	Jamming signal generator	U-700	450-1,000 mc	0.1 w	804, 805	Several modulations available.

13.5.2 Equipment and Films for AJ Training

Table 2 summarizes the equipment developed for AJ training purposes. Several field jamming transmitters were modified for training, special signal generators were developed, and an AJ trainer attachment was engineered.

The practice jammers (AN/UPT-1, AN/UPT-T4, and F-2000) were modifications of regular field jammers and were intended for field use where a sizable power output is necessary. A selection of modulations is available. The RF-9/UPT attachment plugs directly into a tube socket of standard jammers and provides modulations needed for AJ practice. The AJ training attachment TS-109/SPA was developed to meet a need for such a device expressed by the Navy. It is a generator to provide video-frequency jamming signals to the Mark I trainer, which is used to train operators for the Navy Mark III and IV fire-control radar systems. The device will simulate both on- and off-target jamming signals with a wide selection of modulations. The TPQ-T2 signal generator was developed at General Radio Company, and the other equipments at RRL.

The activities in connection with training films consisted partly in the production of prototype training films on AJ and partly in the furnishing of technical consulting services to the Army and Navy on such films. Three prototype films were made (J-2, J-3, J-4), illustrating AJ techniques on the Mark IV (FD) and SCR-521 radars and explaining the use of the E-510 filter. In making these films, considerable work was done in developing techniques for cinematography of radar indicator screens. A considerable amount of assistance was requested by both the Army and Navy in connection with the AJ portions of radar operator training films. The type of consulting varied from film to film but included script editing, advice on photographic techniques, and the furnishing of radar systems and jamming equipment. Films on which RRL acted in a consulting capacity are listed in Table 3.

TABLE 3. AJ consulting on Army and Navy training films.

Equipment	Film No.	Film title	Service	Classification
ASG	MN2867-E	*Radex PPI and B-Scan*	Navy	Confidential
ASB	MN2867-B	*Radex ASB*	Navy	Confidential
Mark IV	MN2867-C	*Pt 1—Radex Fire-Control Radar Equipment*	Navy	Confidential
Mark IV	MN2867-D	*Pt 2—Radex Fire-Control Radar Equipment*	Navy	Confidential
.....	MN2867-A	*Window*	Navy	Confidential
SCR-268	TF-4-1320	*The Radar Set SCR-268, Pt 7—Indicator Jamming*	Army	Confidential
.....	TF-11-1420	*Pt 1—Radar AJ for the Radar Operator—Receiver Adjustments*	Army	Restricted
	TF-11-1421	*Pt 2—Radar AJ for the Radar Operator—Recognition of Electronic Jamming*	Army	Restricted
	TF-11-1422	*Pt 3—Radar AJ for the Radar Operator—Window*	Army	Restricted
AN/TPL-1	TF-44-1456	*Pt 1—The Radar Set—Operation*	Army	Confidential
AN/TPL-1	TF-44-1457	*Pt 2—The Radar Set—Jamming*	Army	Restricted

13.6 CONCLUSIONS AND RECOMMENDATIONS

The very limited extent of the enemy jamming and deception of our radar during World War II made a large-scale AJ effort unnecessary. Sufficient basic work was done, however, to be able to meet AJ emergencies had they arisen. This research pointed up an overall lesson to guide the future of AJ activity and the development of electronic equipment in general.

Perhaps the most important factor is that sound design is the best AJ feature that an equipment can possess. Furthermore, the best place to include such features is in the original design of the equipment. Although it is true that certain of the specialized AJ devices may prove to be useful and necessary under jamming conditions, they will be much more effective if they are incorporated into the design than if they are retroactive modifications. Progress has been made in securing the inclusion of sound AJ design in recently developed radar equipments, and it is hoped that this condition will prevail further in the future.

Of very nearly equal importance as an AJ measure is a well-trained operator for the radar equipment. (This is true also in nonradar fields —see Chapter 9.) This conclusion was borne out

SECRET

very forcibly by the radar system vulnerability studies, which showed that an operator who knew how to manipulate the radar controls in the presence of jamming was able to maintain much higher effectiveness of operation. The fundamental principles of the best operation of radar in the presence of jamming have been well developed in the laboratories, but the education of operators in the field is a continuing problem. Pamphlets, films, and actual practice in operating under jammed conditions were used as training measures by the Armed Services, and all are important. It must be emphasized, however, that there is no substitute for actual practice and that the use of training jammers against operational radar is a vital part of an adequate AJ training program.

Of the total radar development effort in the United States during World War II, only a very small portion was devoted to AJ "doctoring" of existing radar. By far the greater part of the development concerned the application of sound engineering principles to new radar designs and to the best design feature of all the development of techniques to employ ever-expanding frequencies in radars. This is evidenced by the multitudes of new frequencies in use.

Contrast this with the information obtained about the German scientific effort.[806] No research at all on radar was done from 1941 to 1943! When radar research was resumed, the effort was concentrated very heavily (up to 90 per cent!) on trying to salvage the Wurzburg gun-laying equipment in the face of the jamming attack that had already begun. Even though they had captured some British S-band equipment by 1943, no German microwave radar appeared in operation until early 1945, and then in negligible quantities. In consequence, the Allied jamming effort was able to keep ahead of the Wurzburg improvements, a position which would have been very difficult to maintain had the German effort been concentrated on diversified development.

But it should not be assumed that the mere extension of radar designs to higher and higher frequencies constitutes complete freedom from jamming vulnerability. The United States X-band designs were believed safe solely on the basis of their frequency, but an X-band jammer of high potentiality was also developed. Advances in basic h-f techniques and the application of them to operational equipment must be continued and the emphasis *increased* on carrying into new equipment designs the AJ lessons learned from World War II.

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Chapter 14

RCM IN THE EUROPEAN AND MEDITERRANEAN THEATERS

14.1 INTRODUCTION

THE LARGEST USE of radio and radar countermeasures equipment during World War II was in the European and Mediterranean Theaters of Operations. The reasons for this are manifold. The Germans were much better equipped for a technical war than the Italians and the Japanese. Furthermore, they made very good use of the equipment that they had available.

Although radar had been developed independently by England, Germany, and the United States, Allied countermeasures were really started in England, where the necessity of counteracting the German bombing attacks by any means available made the use of radio countermeasures [RCM] very important to the operational planners.

The main body of this report is divided into sections in which RCM in the Air Forces, Navy, and Ground Forces are discussed separately.[a]

This chapter covers the use of radio and radar countermeasures both in the European and in the Mediterranean Theaters of Operations. In this introductory section, a brief summary of the early activities of the RAF is given since it was this early experience in RCM which to a great extent was the basis for commencing the countermeasures program by the U. S. Armed Forces and developmental laboratories. The operational need for RCM and the extent of the aid given by civilians to the Armed Forces in the theater are discussed.

14.2 EARLY BRITISH USE OF RCM

The earliest known use of radar by the Germans was in 1939. The importance of countermeasures was first brought home in World War II during the German raids on England in 1940 and 1941. It is pertinent in this report, which deals with the use of countermeasures by the U. S. Armed Forces, to give a brief history of the use of RCM by the British prior to their use by the United States.

After the fall of France, when the Germans commenced the Battle of Britain with heavy bomber raids on British cities, the Germans set up a large number of navigational systems which were designed to aid in the bombing of England at night. It has often been stated that radar played a very large part in the successful defense of Britain against the day attacks by which the Luftwaffe first tried to bring England to her knees. When the Germans switched to night bombing, countermeasures which were applied against the navigational systems used by the Germans in these night raids were a very important factor in reducing the severity and effectiveness of the bombing.

The German successes in France, the Low Countries, and Norway made it possible for them to lay navigational beams across English targets from a very broad front. The RAF 80th Wing was given the responsibility for countering these navigational systems. Listening stations were maintained along the coast to search for new navigational beams and new frequencies and to locate the stations from which these systems originated. A great deal of information concerning the target selected by the enemy for a particular night was obtained from a study of these signals. Information from these listening stations was immediately transmitted to a central point where the decision was made as to the type of jamming to be used.

The Germans originally used fixed medium-frequency beacons and Knickebein, which was a Lorenz-type beam on 10 m which used the blind approach equipment installed in every German night bomber. Later on the Electra, Ruffian, medium-frequency direction-finding [DF] stations, and the Benito systems came into use. The Electra was a medium-frequency Lorenz beam, whereas the Ruffian was a more complicated Lorenz system on 70 mc with two

[a] Much of the material concerning RCM in the European Theater of Operations [ETO] is also to be found in reference 831, which refers particularly to the activities of the American-British Laboratory [ABL] in connection with the countermeasures program.

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crossbeams giving fine range. A few of these navigational systems were jammed in various ways—for example, with jammers which emitted signals very nearly like those of the system being jammed. The DF systems, however, were rendered ineffective by the use of "meaconing." The ground meacon station picked up the German aircraft transmission on which a DF bearing was being taken and retransmitted it from a point several miles distant from the receiving site. The bearing could thereby be thrown considerably off, and there have been a number of cases where German aircraft were so confused that they landed in England thinking they were in Germany. Considerable success attended all of these countermeasures operations, the enemy crews very often complaining that their sets were out of order and repeatedly requesting DF fixes from the ground stations.

The first use by the British of radio communications jamming occurred in the Libyan campaign which commenced on November 18, 1941. During this operation, the British equipped six Wellingtons with 50-w transmitters to jam the German tank radio equipment, which operated on a frequency of 27 to 33.5 mc. Preliminary tests indicated that all enemy voice and code communications between points which were more than 2 miles apart would be prevented within a radius of 30 miles of a jamming aircraft at 15,000-ft elevation. Prisoners stated that they were usually out of voice or telegraph communications after these operations were commenced. Unfortunately, however, it is impossible to know exactly what were the results of this program because a few days after its initiation all planes involved in it were lost.

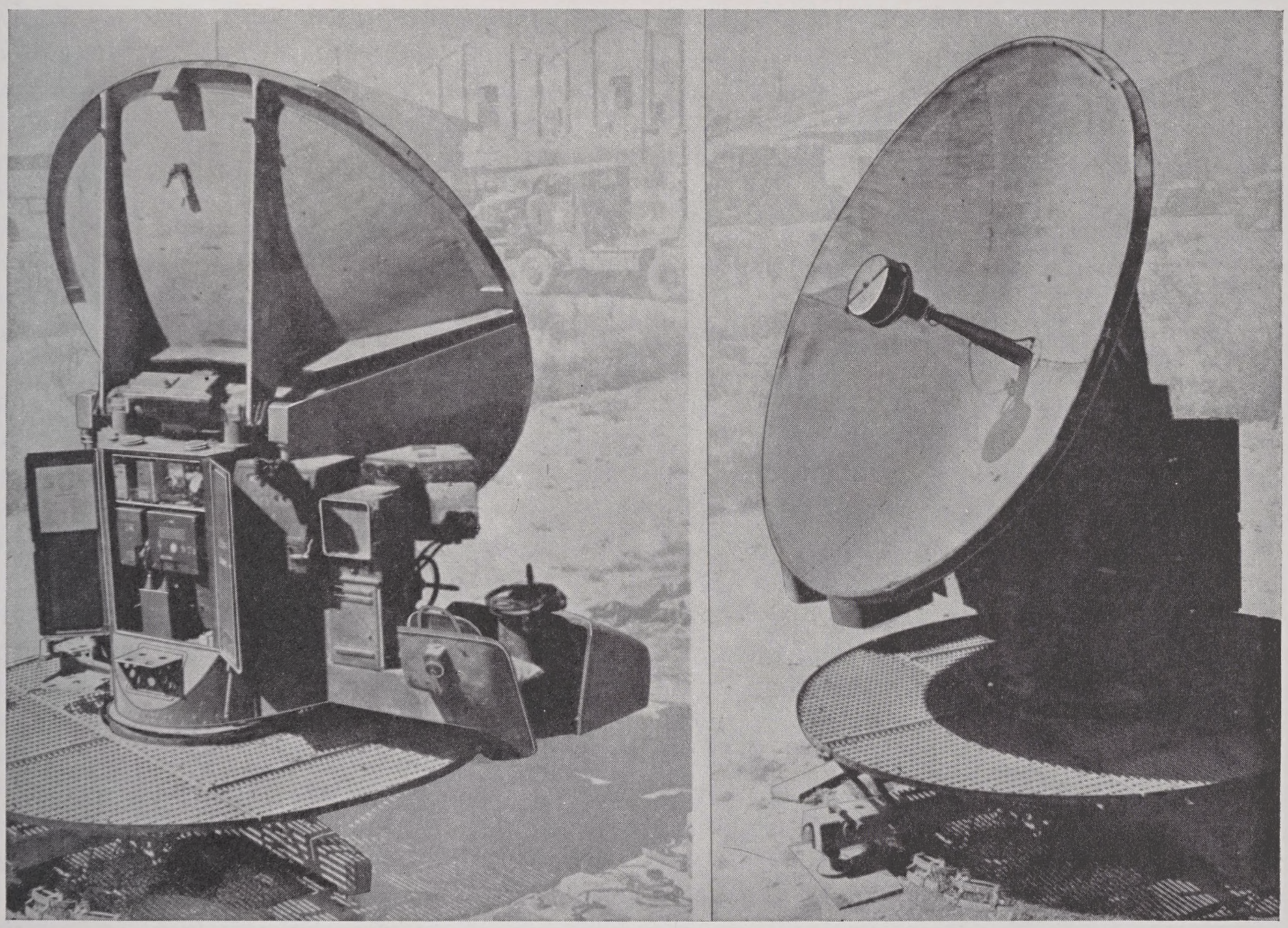


FIGURE 1. Small German Wurzburg—the principal German radar used for antiaircraft fire control.

The Bruneval raid of February 28, 1942, was

primarily undertaken to capture an operating German radar station in order that knowledge concerning the state of developments reached by the Germans in radar might be obtained and to determine the specific characteristics of the German Wurzburg radar equipment which was installed at Bruneval. At that time, the Wurzburg appeared to the British as a potentially increasing threat because of its possible use in controlling searchlights and antiaircraft fire, and as ground-controlled-interception [GCI] equipment. A major portion of the equipment except the indicator system at Bruneval was carried away bodily and suffered very little damage. It was later possible to make the units work in the laboratory at Telecommunications Research Establishment [TRE] without modification or reconstruction. From these tests, a great deal of information concerning the equipment was obtained, making it possible to design jamming equipment much more successfully. This information was of great interest to the laboratories in the United States which were preparing development of countermeasures equipment, with inadequate information concerning the enemy radar and tactics.

One incident which served to accelerate Allied interest in the development of radar countermeasures was the German jamming of the British radar system which occurred during the *Scharnhorst* and *Gneisenau* actions. These ships were berthed at Brest in Brittany, France. The British were very anxious not to let these ships go across the Channel or around England to the northern part of Germany, where they would be a potential threat to Allied shipping. No official history of this action is available, but from informal reports it appears that before the day set for the move German jammers had interfered spasmodically with the British radar system. The British operators did not recognize that the jamming was genuine, or if they did they were not greatly concerned because no unusual operation was connected with the jamming. One day in bad weather all the German jammers which had previously been tuned and set on the proper frequencies, jammed all the British radar systems of which the Germans had knowledge. It is not known whether the air-to-surface-vessel [ASV] radar of the British patrol planes, which were supposed to determine whether the ships left the port of Brest, were also jammed because most of the planes were lost. The fact is that the ships were not detected until after they had come around the Brittany peninsula and were well on their way through the channel.

Some of the British radars noted the unusual German air activity which, unknown to the British, consisted of aircraft escorting the ships, but because of organizational difficulties no attention was paid to these aircraft until a British naval aircraft saw the ships and sent an urgent alarm. Air attacks were hastily organized and the Dover coastal batteries informed, but it was too late. Many of the old Swordfish torpedo planes which attacked the ships were lost but little if any damage was inflicted on the German ships. This operation was indeed a warning to the British, who at that time had 60 per cent of their radar on one frequency and were therefore extremely vulnerable to enemy jamming. It also made high-level authorities and officers aware of the danger of countermeasures and spurred the effort of both British and American research establishments in the search for effective countermeasures and antijamming [AJ] devices. The *Scharnhorst* and *Gneisenau* action can be considered a turning point in the history of countermeasures. After that there was no question that determined effort was necessary in the development of countermeasures which had been proved so effective when used against Allied sets. Paralleling the development effort, a training program for radar operators was also initiated to alert operators against the dangers of jamming and to teach them to distinguish intentional enemy jamming from defective operation of their sets.

The British first used radar jammers to jam the German coastal radar which was being employed by the enemy against Allied shipping in the Strait of Dover. The jammers were located on the Dover Cliffs and used railing (pulse) type modulation.

Towards the end of 1942, a very different type of RCM was employed by the British against the German 120-mc early-warning [EW] radar. It is described here in some detail

because it is important to show that there is more to RCM than jamming and search. This operation was carried on by Moonshine equipment, which was an airborne radar countermeasure by means of which a few planes appear to the enemy radar as a large raid. The Moonshine is designed to increase the amplitude and duration of the echo returned from the aircraft, thus making it appear to the radar that many more aircraft are present. Such equipment was used on several occasions where a diversion was required, especially in support of Eighth Air Force raids, and was also employed by the RAF fighter command in an attempt to bring up enemy fighters. During this period, enemy fighters avoided conflict except on highly favorable terms when Allied bombers were sent over. Fighter sweeps by the British were generally unsuccessful and Moonshine was used in an attempt to improve their success. The adoption by the Germans of their 550-mc Wurzburg equipment for EW caused the use of Moonshine, which had not been developed for use on that frequency band, to be dropped. The British were afraid that the use of Moonshine would be compromised if the Germans were able to check up on the size of the raid by the use of the Wurzburg. In a normal Moonshine operation, eight Defiants flew with a fairly large group of fighters in towards the enemy coast. When approximately 30 miles away, the Defiants left the fighters, dropped down nearly to sea level, and proceeded home at a very low altitude, where they escaped radar detection. The effectiveness of Moonshine was never completely determined and since a large number of fighters were always sent with the bombers it was never certain whether the use of Moonshine was a particularly important factor in causing the Germans to believe that a large raid was approaching.

After the RAF night raids were started the British became greatly concerned over the use by the enemy of ground radar for the control of night fighters, antiaircraft fire, and searchlights. The Freya radar at that time was the equipment most used by the Germans against the RAF, although later the Wurzburg became an important part of the German defenses. The British designed and built an airborne jammer which was known as Mandrel to cope with the Freya radars. The Mandrel was the first jammer which used noise modulation and was used with considerable success throughout the rest of World War II.

14.3 SCOPE OF OPERATIONAL USE OF RCM BY U. S. ARMED FORCES

Radar countermeasures played a considerably more important part in World War II than radio countermeasures. Radar countermeasures were of more importance to the U. S. Army Air Forces than to any other branch of the Armed Services, since the enemy radar was used against our aircraft to a considerably greater extent than against any other type of attack.

Heavy bombing was commenced by the Eighth Air Force in August 1942, and in the North African campaign in early 1943. Blind bombing was started by the Eighth Air Force in November 1943 and from then on was used in many of the raids. After this, approximately 55 per cent of all Eighth Air Force attacks were made during blind bombing conditions. Radar countermeasures were of greatest use to the Air Force during such attacks, because the enemy was forced to rely entirely on radar for flak-control information during such operations and did not have visual range- and direction-finding methods to fall back on.

For reasons that will be explained in a later chapter, countermeasure techniques were not of great value in solving the fighter problem.

Heavy bombing was commenced against Italian targets in the fall of 1943 from bomber bases located in North Africa. At the beginning of 1944, the Fifteenth Air Force was formed and, when strategic bases were developed in Foggia, the heavy bomber offensive was made considerably more effective. The problems of the Fifteenth Air Force, in so far as RCM was concerned, were quite closely allied to those of the Eighth Air Force, since both air forces were attacking a common enemy and in some cases were even attacking the same target. There were certain differences between the radar equipments and techniques used in the Italian Theater and those used in Germany,

since in general the Germans concentrated their best type of radar and largest numbers of equipment within the homeland. The similarities were such, however, that in this report no attempt will be made to duplicate discussion of RCM problems which apply equally well to both theaters.

The strategic air forces made far more extensive use of RCM than did the tactical air forces. There were two reasons for this. The first was that the tactical air forces, by the very nature of their job, ordinarily attacked targets which were not as well protected in terms of guns and radar equipment as the heavily defended strategic targets. Secondly, the size of the medium bombers made the use of additional RCM equipment, which was often bulky and sometimes required an operator, rather difficult to handle. Very little use was made of electronic jammers by the Ninth, First Tactical, or Twelfth Air Forces. All three air forces, however, made considerable use of the confusion reflector, Window.

As previously stated, countermeasures were not used to a large extent by the ground forces; however, there were a few cases in which countermeasures were employed, such as during the battle of the Ardennes when aircraft of the Eighth Air Force were used to carry jammers over the battlefield to interfere with enemy tank communication.

Radar countermeasures were used extensively by the Navy, whose units conducted search, for instance, against enemy submarines and used RCM as a means of protection against enemy detection and radar-controlled fire. Radar deception was used as a powerful weapon in many operations. Also, RCM was used with apparent success against the enemy guided missiles.

14.4 U. S. CIVILIAN AID TO THE ARMED FORCES

In the spring of 1942 the director[b] of the Radio Research Laboratory [RRL], went to England to study the British RCM program. His findings were of great importance in determining the initial direction that was taken by the American RCM program.

Since our own Air Forces had not at that time commenced operation in the field, it was only natural that most of the thinking was devoted to the types of problems and solutions that were of concern to the RAF. In November 1942, six junior scientists from RRL and Radiation Laboratory [RL] were sent to work in the British RCM laboratories for a period of about 6 months in order to become familiar with the work that the British were doing. The American Air Forces, during this period, found that they needed help in the countermeasures field, and, since no American facilities were available in the theater, they turned to the British for assistance, particularly to the Royal Air Force and to TRE. The latter assigned one of the American research men to the Eighth Air Force, but at the same time they felt that this American radio countermeasures effort in the operational theater was disproportionately small when such a large effort and so much manpower were available in the United States. As a result of this need and the observation of a mission of United States scientists, the American-British Laboratory (see Figure 2) was set up in August 1943, through a contract from Division 15 of the National Defense Research Committee with Harvard University. This laboratory was set up to aid the U. S. Armed Forces in the European Theater of

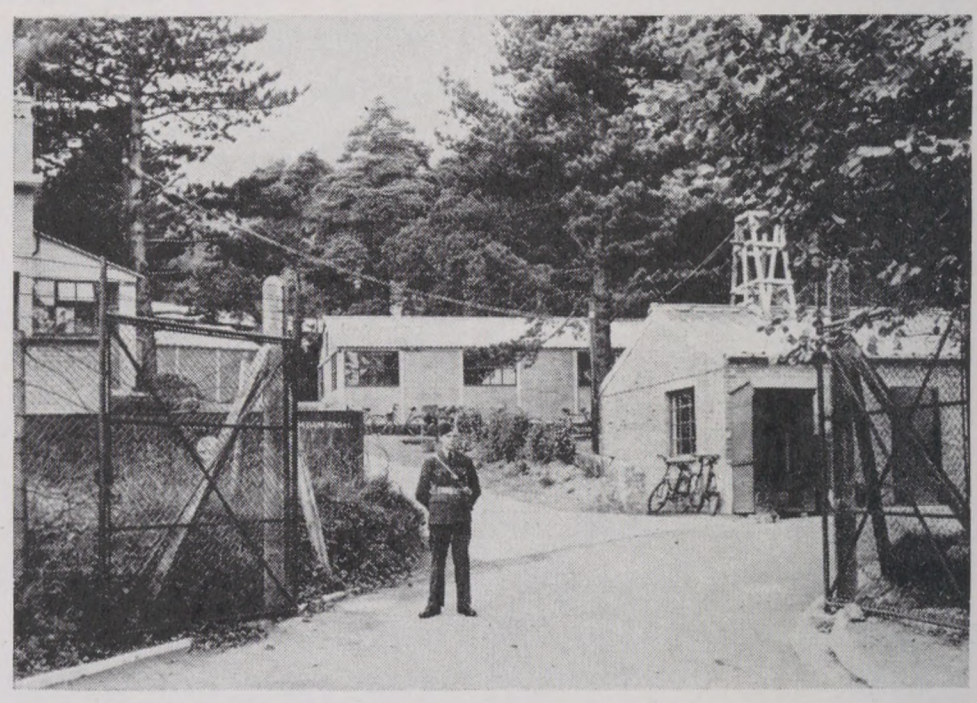


FIGURE 2. The American-British Laboratory, Great Malvern, England, which operated under contract OEMsr-1045 from Division 15 of the National Defense Research Committee.

[b] Dr. F. E. Terman.

Operations [ETO] in their use of RCM equipment and techniques. The laboratory grew to about 70 people and remained in operation until the end of the war in Europe. This laboratory engaged in work for practically all branches of the U. S. Armed Forces, including the Navy, the Air Forces, and the Ground Forces.

No civilian laboratory was ever set up in the Mediterranean Theater of Operations [MTO]. Instead, a number of civilian technical observers were sent from RRL to aid the Air Forces in the use of RCM. The first of these observers arrived in the MTO in April 1943, when the RCM program was being started. A total of 17 technical observers from RRL or ABL-15 were sent to the MTO, and at the end of World War II seven men were stationed with the Fifteenth Air Force or with MAAF to help with RCM problems.

14.5 RCM IN THE U. S. AIR FORCES

14.5.1 The Operational Problem

After the beginning of daylight bombing, the German defenses consisted of daylight fighter attacks and of antiaircraft artillery. The fighter threat was particularly serious at the beginning, so much so that at the end of 1943 the Eighth Air Force had to limit its activities for two or three months to shallow penetrations until long-range fighters became available. (At this time, the Fifteenth Air Force had just been formed from the heavy bomber groups of the Twelfth Air Force.)

Starting in February 1944, a full-fledged offensive began against the Luftwaffe, both by bombing of aircraft factories and by aerial combat. From March 1944 on, the whole strategy became one of engaging the enemy aircraft under any circumstances, favorable or unfavorable, with the purpose of shooting down as many as possible. This strategy influenced the countermeasures activities in support of the strategic air forces, because no requirement then existed for preventing the enemy from knowing the time, direction, and target of our attacks. Heavy losses due to fighters were suffered by the AAF in early 1944; but thereafter the fighter losses decreased continuously as is shown in Table 1, taken from Eighth Air Force operations.

It will be seen that, although fighters were responsible for the major losses in 1942 and 1943, during the remainder of World War II the flak problem became the more serious. The increase in losses towards the last part of the war is, of course, due to the increased weight of attack and does not represent a greater percentage of losses. Although not shown in this table, the number of enemy aircraft shot down increased continuously, and at the same time the number of operational sorties by the enemy decreased, presumably because of lack of oil and trained pilots.

TABLE 1. Eighth Air Force Losses.*

Period	Lost to flak	Lost to fighters
Aug 1942 to Jan 1943	5	25
Jan 1943 to July 1943	166	500
July 1943 to Jan 1944	165	518
Jan 1944 to July 1944	847	637
July 1944 to Jan 1945	1,320	438
Jan 1945 to end of World War II	248	92

* Figures only approximate.

The threat created by the German fighters against the strategic bombers based in the MTO became particularly serious when the heavy bombers went to bomb targets in Germany. However, the distance between the front lines and the targets was such that no effective jamming of the enemy EW system could be conducted with any hope of substantially decreasing the fighter threat for the deep penetration missions. In the MTO, as in the ETO, after the fall of 1944, flak was by far the major cause of loss due to enemy action.

FLAK RCM

With the progress of our ground forces, the area to be covered by the available enemy flak guns decreased steadily and the density of the enemy flak defenses increased correspondingly until at the end of 1944 as many as 15,000 heavy guns had been counted on the German-controlled territory.

Fighting against flak guns is a difficult task. and, whereas tactical air forces (particularly

the Twelfth Air Force) occasionally bombed flak batteries with some success, the strategic air forces had to rely mainly on passive defenses and on radar countermeasures. To the men responsible for deciding the operational tactics of the Eighth and Fifteenth Air Forces, several possibilities were presented as a means of decreasing the flak risk. One of them was RCM, about which this report will deal specifically. However, the picture as a whole should first be presented in order that any single aspect may then be seen in proper perspective.

The type of formation flown and the way these formations navigated, especially near the target area, very greatly influenced the flak risk to which the bombers were exposed. In the early months of 1944, the bombers were flying in squadrons or boxes of 18 aircraft, and frequently three of these squadrons were flying together, so that it was often possible to see combat wings or attack units of 54 aircraft. The reason for this was that guns in the bombers were the only defense against enemy fighters and crossfire protection was necessary for an effective defense. Formations of this size were very unwieldy and required high skill on the part of the pilots. Furthermore, they were the ideal targets for a flak battery. The reason for this is clear; if a shell is aimed at the center of a combat wing of this size, it can hardly miss even if the aiming error is relatively great. Decreasing the size of the formation was, therefore, the first aim as soon as the losses from flak began to exceed those from fighters. This could be done only to a limited extent because making maximum use of the few available blind bombing devices had led to the technique of dropping bombs with only one sighting operation made by the lead bombardier. The necessity of any significant reduction in the size of the formation was delayed until July 1944, and even then the size of the squadron still remained far from ideal.

Another method of reducing the flak risk is to increase the concentration of attack so as to have as many aircraft as possible fly over the target in the minimum time. Formation flying is a difficult business, as prop wash and condensation trails prevent squadrons from flying too close together. These difficulties were considered very important. Despite this, all possible efforts were made to increase the concentration as much as possible and several wings in the 8th and 15th Air Forces tried special tactics with some success.

Evasive action has been long recognized to be a very effective countermeasure against flak and the same can be said of downwind flying (to increase the relative ground speed); but, although these methods decrease the flak risk, they bring about a loss in bombing accuracy. This means more bombers or more missions are needed to do the same job. For these reasons, no evasive action was taken by the strategic bombers although bombing was often done down wind. Armor plate and other devices could be designed to reduce the vulnerability of each bomber, but in the ETO the increase in weight and the nonavailability of the necessary equipment prevented this trend from going very far.

Altogether, therefore, from the point of view of the strategic air force, flak remained a threat against which it was difficult to take positive countermeasures. For this reason, the possibility of using RCM was very favorably considered, even if some doubts existed as to its effectiveness in visual missions. The problems inherent in the installation of a large number of RCM sets in some 5,000 aircraft and in the use of a proportionally large number of bundles of Chaff appeared less difficult than changes in the long-established operational techniques employed up to that time.

Another consideration which made RCM attractive was that reduction in the flak risk would enable operational planners to assign lower flying altitudes to the bombers without undue increase of the danger to which the aircraft would be exposed. With the decreased altitude, a higher bombing accuracy would be obtained, and therefore the number of sorties required to knock out a target would be proportionately reduced.

The tactical air forces in the ETO and MTO did not make important use of electronic jamming. Although there were early experiments with Carpets in the Ninth Air Force, these were on a very small scale and could not have been an important factor in influencing losses.

The strategic air forces were always given

priority on RCM equipment, and it was not until early 1945 that Carpets became available in quantity to the tactical air forces. At that time the possibility of using Carpets was considered by the bombardment division of the Ninth Air Force, but for a number of reasons, including the fact that the air force was in the process of shifting from B-26's to A-26's, it was decided not to use electronic jammers. Henceforth, consideration of RCM assistance for the tactical air forces involved the integration of either spot- or barrage-jamming installations into an A-26 aircraft. Because of the small crew complement of this aircraft, manual spot-jamming installations were ruled out. Even if space and weight had been available to carry transmitters, receiver, and operator (an additional load which probably could not have been accommodated), it would not have been desirable to add an additional man to a two-man crew, since the resulting 50 per cent increase in crew complement might have resulted in increased personnel casualties even if aircraft had been saved. Barrage-jamming calculations undertaken independently in the field and at the laboratory indicated that at best no more than 30 to 40 per cent of the dangerous radars could have been covered. This conclusion was based on Ninth Bombardment Division operations, where the maximum force to be considered as a unit for self-protection was the 16- to 18-plane box. Thus, protection from one-third of the dangerous radars was not considered sufficient to warrant the effort of barrage installations, because of the small number of aircraft whose loss could be attributed to radar-controlled flak fire. Spot jamming would obviously have provided better protection to the medium bomber forces with considerably less effort, but space and weight limitations of the A-26 aircraft ruled out such a plan.

Repeated requests for the numerical evaluation of the effectiveness of RCM were made to the RCM civilian personnel both in the ETO and the MTO. A great deal of work was done in attempting to answer these requests. After some already elaborate analysis, a coordinated effort was begun in the Eighth Air Force to analyze the battle damage figures in a way which would take into account the effect of almost all of the important parameters. The result of this work was unsatisfactory and no numerical evaluation of the effectiveness of RCM could be supplied. The battle damage figures proved to be too inconsistent to allow drawing definite conclusions. In the MTO, on the contrary, work conducted on similar, even if less thorough, lines, appeared to give more consistent results, at least during the summer and fall of 1944. It was, of course, definitely established that RCM was effective and an attempt was made to measure quantitatively its effectiveness. Because of the controversial nature of the comparison between the ETO and MTO methods of analysis, it is considered beyond the scope of this report to summarize the results obtained in the MTO. It is sufficient to say that tests against captured equipment, the effect of radar countermeasures when employed against our own equipment by ourselves or the enemy, and the attempts by the Germans to develop AJ devices, together with intelligence reports, were actually the only definite proof available before V-E Day of the usefulness of the recommended tactics and RCM installations.

Fighter RCM

The effective defense of Germany and German-occupied territory by the enemy fighters was based on a well-developed radar network, very-high-frequency intercept stations, ground observer groups, spotter aircraft, and intercept stations which devoted their attention to special signals like Carpet or airborne radar. All these sources of information were coordinated and contributed to give to the headquarters of the enemy fighter defense a complete picture of the air attacks even before the bombers left the vicinity of their bases as well as during the attack itself.

Control of the fighters from the ground stations was carried on during the winter of 1944 by means of h-f and v-h-f transmissions. In single-engine day fighters, very high frequency was used exclusively, the v-h-f equipment being used for normal voice communications and Benito control. It is clear that interfering with enemy communications, especially with the air-to-ground and ground-to-air channels, was a promising approach to defensive tactics. Jam-

ming of communications, however, is intrinsically much more difficult than jamming radars and it requires more powerful transmitters.

Another approach to defense against fighters was to interfere with the radar network so as to decrease the amount of information available to the enemy controllers. Here again the multitude of frequencies used by the enemy for the purposes of early warning and the large network of radar stations existing along the Channel, the Dutch coast, the Adriatic Sea, northern Italy, Yugoslavia, and inland made the problem of screening the bomber formation from radar detection difficult.

Despite the difficulties of countermeasures against the radar network and fighter communications, the RAF managed to throw the enemy system out of balance successfully in a large number of operations.

Tactics peculiar to the RAF made this possible; the RAF flew at night with single aircraft distributed along a bomber stream, so that less jamming power was required against the enemy radar and no visual ground observation was possible. A special group (slightly bigger than an American wing) was devoted by the RAF to countermeasures. Without going into details which would be outside the scope of this report, it might be mentioned that, altogether, they were quite successful against early warning, GCI, and even *aircraft interception* [AI]. The reasons why such a program was never duplicated by the USAAF are simple and worth considering at this point.

First of all, AI did not represent a menace to daylight bombers; second, it appeared practically impossible during daylight over enemy territory to create deceptions whereby one group of ten planes was made to look like a whole bombing raid. Furthermore, when fighter escorts became available, the intent of the air force was to meet and fight against the enemy aircraft, and therefore there was no desire to prevent the enemy from knowing the location of our bomber formations. Even in the late months of 1943 and the first two months of 1944, when long-range fighter escorts were not present and the enemy fighters represented a serious menace, radio and radar countermeasures could hardly have been sufficient to protect the formations against fighter attacks in unescorted deep penetration raids, which were the ones on which the danger was serious; besides, the amount of RCM equipment available was extremely limited.

Another reason which made it difficult to carry on an effective RCM program was that much useful intelligence could be gathered by listening to the enemy communications and here, as in most theaters of war, a conflict existed between the people who wanted to jam the enemy communications and the people who wanted to listen to them in order to get intelligence.

To summarize, when the fighter menace was great, at the end of 1943 and the beginning of 1944, the lack of equipment and the practical impossibility of carrying on fighter countermeasures from the available bases, limited the use of RCM by the American Air Forces as a means of protection against fighters. From the spring of 1944, the whole strategy against enemy fighters changed, and, despite the fact that more equipment had become available and new bases had been obtained, both radio and radar antifighter countermeasures were found to be inconsistent with the general operational doctrine of the strategic air forces.

The above statement applies only to the jamming of the enemy EW radar network and the enemy communications systems; other types of RCM work which were dictated by the changing air situation were undertaken. For instance, at the end of 1944, it was found that the enemy was getting too much intelligence by listening to our v-h-f chatter and steps were taken by the Eighth and Ninth Air Forces to jam our own v-h-f frequencies during the assembly over England by means of aircraft which were flown close enough to the enemy listening stations and far enough from England to prevent the enemy H-Dienst (intercept system) from working properly, without interfering at the same time with the communications between our bombers and between the bombers and the ground.

When the air supremacy was established in such a way that finding enemy fighters to fight against became a serious problem, work was started on building equipment capable of interrogating and DF-ing on the enemy identification

friend or foe [IFF] in order to guide Allied fighter groups on to enemy fighter concentrations. Furthermore, when at the end of 1944 and at the beginning of 1945 jet planes appeared as a potential danger, work was started again in the ETO on a radar screen just as a measure of insurance in case the whole U. S. fighter strategy had to be changed. The work was done in the first month of 1945 along the same lines followed in the early months of 1944 for the same purpose but in a better way. Except for a few days of operation which will be described later, this screen was never used and World War II ended before jet planes were ever used in large quantities by the enemy.

The history of the whole effort against German fighter defenses by the U. S. Strategic Air Forces is one of uncertainty, with projects started and left not completed because of changes in the strategic situation. In this part of the RCM field more than any other, the importance of a close liaison between the operational planners and the technical people appears fundamental. There is perhaps nothing more striking than the contrast between the RCM work carried on by the RAF, the largest part of which was directed against enemy fighters, and the RCM work carried on by the American Air Forces, which was almost entirely antiflak.

Another type of work in which the RCM personnel were involved both in the civilian laboratory and in the Strategic Air Forces was the problem of airborne interception of enemy communications. This was essentially a function of intelligence; the intelligence sections of both the RAF and the Eighth and Fifteenth Air Forces did make use of the results obtained, but in the Eighth Air Force the technical side was handled by RCM personnel because of their experience with radar search and with techniques of a similar nature even if on different frequency bands. In the Fifteenth Air Force, the technical side was handled by radio personnel, with a small amount of assistance from RCM personnel.

The old problem of intercepting enemy communications for the purpose of gathering information on the enemy order of battle and on the enemy reaction to bomber raids was started by the British Air Ministry, which developed a very well-organized and smoothly operating organization which intercepted enemy transmissions and accurately DF-ed on them. Most of the intercept material available to these units came from ground receivers. It was clear, however, that ground reception did not give a clear picture of all the events inside Germany and, when the knowledge of such events was obtainable only through listening to the enemy v-h-f communications, airborne interception had to be employed.

14.5.2 Capabilities and Limitations of the RCM Available

RCM officers and technical men working in RCM had two main lines of attack against enemy gun-laying [GL] radar. The first one was Chaff; the second, Carpets. Before giving details on these two countermeasures it must be noted that they act against the enemy radar sets in a completely different way. Chaff and Carpet have characteristics such that the combined use of the two at the same time presented the enemy with a problem which was much more serious than the one presented by the use of Chaff or Carpet alone. Actually, we know now from Intelligence, and we knew before from our own experience, that against a full-scale, well-organized RCM program of this type, the designer of the radar set has only one solution: to build another set in a completely different frequency range. The Germans attempted that but were too late.

Chaff

It is well known that a large quantity of Chaff can so infest an area that any aircraft flying near by is shielded against detection by any radar set whose frequency is near the one for which the Chaff is cut. If, therefore, our formations had been flying the ideal briefed course with all formations one behind the other in a continuous stream, only the leading formation would not have had the full protection that the Chaff could offer. Unfortunately, especially on blind missions, the distance between the tracks of the different squadrons or groups was such that not more than 10 to 30 per cent

of the aircraft participating in the mission flew close enough to the Chaff trails laid by preceding formations to take advantage of the full protection offered.

In any case where a formation drops Chaff and is *not* near a trail, a skilled radar operator can often (still) track it by looking at the leading edge of the trail left behind. However, this operation requires a highly skilled crew, particularly in the case of the German Wurzburg, which is not equipped with a plan-position indicator [PPI]. Furthermore, tracking of this type becomes more and more inaccurate when the target approaches the crossing point[c] of the battery; the inaccuracy increases when the amount of Chaff increases. Furthermore, when the target is being bombed by a force of, say, 1,000 aircraft, the region over the target is so full of Chaff after the first 200 or 300 have gone by that it is extremely difficult for the operator to find a target even if he can track it once it is found.

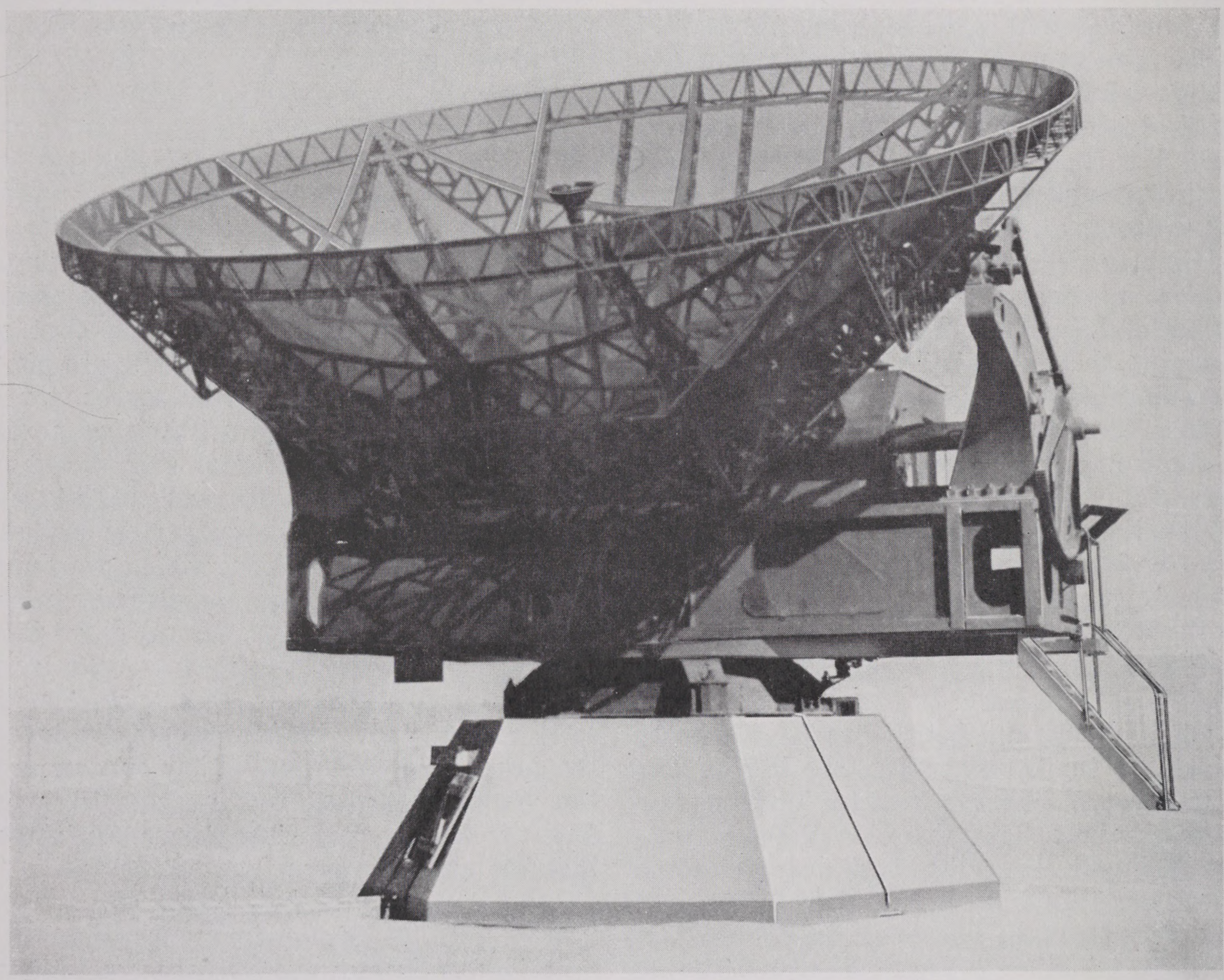


FIGURE 3. Giant Wurzburg used by the Germans for purposes of antiaircraft fire control and fighter direction.

[c] Crossing point is, by definition, the point which is closest to the battery along the course of the aircraft, which is assumed to fly straight and level.

In conclusion, it appeared, therefore, that two things could be done to improve the effectiveness of Chaff. The first one was to increase as much as possible the amount of Chaff dropped; the second, to increase the concentration of the attack, and at the same time to increase the precision with which each aircraft followed its predetermined track.

Antijamming devices have been developed by

SECRET

the Allies as well as the Germans which make it possible for a radar set to distinguish between essentially stationary Chaff and actual moving targets. These methods are based on the fact that, with respect to the radar location, Chaff does not usually move at the speed of the aircraft. The doppler effect can therefore be used to find a moving target in a cloud of stationary Chaff. It was natural to find the enemy reacting to our use of Chaff by developing AJ devices of this type. Increasing the amount of Chaff dropped was a partial answer but certainly not a perfect one. It will be shown later that no such AJ device can work satisfactorily if effective electronic jamming of the type supplied by Carpet is present at the same time. This is one of the ways in which the combined use of Carpet and Window becomes more efficient than the use of either one alone.

Chaff was packaged in bundles, each containing enough strips of aluminum to simulate either one or three heavy bombers, depending on the type of Chaff. In order to drop enough Chaff to simulate a continuous stream of aircraft, one "unit" of Chaff (one unit simulates one heavy bomber) must be dropped for each "round-trip pulse length" of the enemy radar. Since the German Wurzburg has a 2-μsec pulse width, each aircraft should drop one unit each 1,000 ft, about 5 units a mile, about 20 units a minute. In order to give an order of magnitude of the quantity involved, if 20,000 sorties were flown in a month and the Chaff was dropped for, say, 20 min over the target area, 8,000,000 units were required per month, which meant a total weight of about 600 tons of aluminum a month.

Carpets

Three types of Carpets became available from the fall of 1943 to the end of World War II. The first, AN/APT-2, is better known as Carpet I; the second, AN/APQ-9 (Carpet III), is more powerful than AN/APT-2 but covers a more limited range of frequencies; the third, AN/APT-5, is still more powerful and covers a wider range of frequencies than either one. The APT-5 arrived in the ETO too late to be used in any significant quantity. The APT-2 was the only set available in the first half of 1944 and was rapidly replaced by the APQ-9 when this became available during the fall and winter of 1944-45.

Carpets, as well as most of the other electronic jammers in use against enemy radar sets, can be used in two different ways, known as barrage jamming and spot jamming. In the former method, the Carpet frequencies are adjusted so as to cover an enemy frequency band as evenly as possible with no holes in the barrage, whereas in the latter an operator with a receiver manually tunes the equipment to the enemy frequency.

In the fall of 1943, a small number of Carpet I's were available and the German sets occupied a frequency band from 560 to 580 mc. Rough calculations and actual tests made in this country showed that a barrage of Carpet I's, with a spacing of about 1 mc between adjacent carriers, could effectively shield 18 aircraft. This meant that if each aircraft in an 18-plane box had one Carpet, the frequency band covered could be made equal to the enemy's frequency band. This procedure was followed in the two groups which could be equipped at that time.

It is to be noted here that the basis for such a program was a certain number of aircraft per unit to be protected, a certain frequency band occupied by the enemy sets, and, finally, a certain spacing for one barrage. Any change in these three fundamental elements would have necessitated radical changes in the plan. Changes did come in all these three basic elements. As mentioned before, the size of the formation decreased; the enemy, alerted by our jamming, took the obvious countermeasure of spreading the frequency band, and, finally, the more powerful APQ-9 set became available. Without a discussion of the intermediate steps, it can, therefore, be seen that a new situation arose at the end of 1944 with the enemy covering a frequency band of 510 to 590 mc and with the size of the squadron which was to be protected varying from 18 to 12, and sometimes 9, aircraft.

The problem of establishing a correct RCM plan was made difficult, notwithstanding the fact that with the new APQ-9 set and the smaller formations, spacing of 1½ and later 2 mc was shown to be acceptable. During the

SECRET

summer of 1944 the shortage of RCM sets had compelled the adoption of a spot-jamming program because, for obvious reasons, spot jamming is the system which enables the most efficient use of RCM sets to be made. In the month of September 1944 with the large numbers of RCM sets available, a solution was found involving the combined employment of barrage and spot jamming in every group of the Strategic Air Forces. The details of this program and reasons which led to its initiation will be given later in this chapter.

The important point here is the fact that any RCM program is very closely connected with the type of formation flown, the distance between the different formations, the type of target that these formations are going to attack, and the enemy's radar tactics. It is clear, for instance, that if a target is defended by approximately 200 guns and the enemy has available one radar set for each 10 guns, there is a maximum of 20 radar sets potentially dangerous to this formation and possibly 10 which will be looking at the same time at each squadron. Furthermore, if squadrons are widely separated it is impossible to assume any mutual help between the jammers carried by one squadron and those carried by a following one. Consideration of factors of this type was necessary to establish the air force RCM plans.

Some general considerations regarding the mutual advantages and disadvantages of barrage and spot jamming should be mentioned here. Barrage-jamming equipment is pretuned on the ground, does not need special operators, prevents the use by the enemy of small frequency changes to avoid the jamming signal, and is altogether a better system, but it requires a large number of sets and sometimes a prohibitive number when the enemy frequency band becomes too wide. Spot jamming is in principle a very efficient method but it suffers very greatly by the fact that the human element plays such an important part in its success. Furthermore, the introduction of an extra man in the crew of each aircraft produces operational problems which are not always easy to solve. Finally, with spot jamming, there is always a danger that two or more operators may be jamming the same signal while another signal is tracking the formation undisturbed.

The training given to the spot-jamming operators in the average group of the Eighth Air Force was essentially a function of the interest shown by the RCM officer of that group in such a program. Spot-jamming operators were usually gunners who represented surplus personnel because of the reduction in the crews of both B-17 and B-24 bombers from ten to nine members. Spot-jamming operators were given an initial training of 4 days in a course which was organized at the 36th Squadron. The intelligence level of the students and the length of the course was such that it was impossible to expect a perfect job to be done. In the groups in which training was continued and intensified through the cooperation of the RCM officer, the efficiency level was reasonably high but it must be recognized that the quality of the personnel, overall, was insufficient to guarantee anything more than a mediocre performance.

The above considerations point out an important lesson, namely, that when the solution of a problem depends so much upon the human element, the same amount of attention should be given to the quality of the operating personnel and to their training as is given to the development and construction of the actual set. Failure to do so, due to the lack of Military Occupation Serial [MOS] number or lack of Table of Organization [TO] openings under the Army organization, cannot but decrease the effectiveness of any even perfect effort on the part of the engineer who designs the equipment, installs it, and plans its operational use.

One important limitation of electronic RCM is the following: The enemy could DF on the jamming signal, if he wanted to, and guess the altitude, which was relatively constant in the 8th Air Force and 15th Air Force attacks. Then he could use this information[d] to do continuously pointed fire; fire controlled through this procedure would not be so accurate as fire obtained with an unjammed radar, but it would still represent a serious danger. Admittedly, if a formation used Carpets and dropped Chaff at

[d] Actually, in a predictor the operator can roughly determine the altitude by so "cranking in" range data as to make the altitude constant, even if he does not know its value.

the same time, the danger of DF-ing on the jamming signal would be greatly decreased, which is another reason why the combined use of Carpet and Chaff increased the usefulness of the total RCM effort. As a matter of fact, however, there appeared no real reason why the enemy could not turn off the transmitters, thereby eliminating the Chaff echoes, and use the angular information obtained from the jammer to control their guns. It is remarkable to note that all these fears were unfounded and that information gathered after V-E Day proved that the enemy did not resort to such tactics. On the contrary, emphasis was given in all the official documents to the requirement for the radar operators to try to "read" through the jamming in order to locate the target. The reasons for this are not very clear. Actually, the enemy did rely on information obtained by DF-ing to plot the course of the formations; the same procedure, however—while inaccurate—would have been better than nothing in the control of fire, and "nothing" seems to have been obtained many times by the German operators.

14.6 THE OPERATIONAL USE OF RCM IN THE MTO

14.6.1 Search and Investigation

A knowledge of the technical characteristics of the enemy radar set is a necessary premise for any RCM program. For this reason, in the MTO, as in any other theater of war, RCM search and investigation began long before an effective offensive RCM effort was decided upon. The first Ferret aircraft with specially trained officers and one civilian observer from RRL was requested in late 1942, as soon as high-level operational officers became conscious of the existence of German radar and of its dangerous potentialities. The Ferret left the United States for North Africa about May 10, 1943. At the time of its arrival, radar investigation in North Africa was being carried on by a few British aircraft of the 192nd Squadron. The coordination of the search activities of the U. S. and of the RAF aircraft was fairly easy. However, serious difficulties were encountered by the personnel of the first Ferret and also subsequent Ferrets, because of the lack of a clear organizational setup for radar reconnaissance aircraft within the standard U. S. Air Forces organization chart.

During the first month, Ferret aircraft devoted their efforts to a search for enemy signals around Sicily, which was due to be invaded a short time later, specifically on July 9, 1943. These first flights were extremely useful in giving to the flying personnel experience in the determination of the best operating procedures. It was soon found that DF antennas were necessary and several attempts were made to improvise some kind of satisfactory system within the theater. Actually the first Ferret had one Tail receiver capable of giving homing indications, but the development of methods of pinpointing stations without flying straight in their direction was found necessary. Until developments, which started in the United States, were completed, both the British and American aircraft had to limit the scope of the search to the determination of the general position of the enemy stations, obtained by flying low and determining the point where the signal was strongest. This method, even if not completely satisfactory, did give to the intelligence agencies a fair idea of the general deployment of enemy radar stations.

It did not permit, however, the determination of sites of enemy stations accurately enough to pinpoint them for the purposes of photographic reconnaissance. In a few cases stations were pinpointed with the Tail homing receiver mentioned above.

Around the month of September 1943, the initial organizational difficulties involved in the establishment of a radar reconnaissance squadron were partially cleared. The Table of Organization of the Sixteenth Reconnaissance Squadron was used for the radar search aircraft and the squadron itself was put under the operational control of the headquarters MAAF. This setup was found satisfactory and lasted until the end of World War II. The squadron undertook the planning, flying, and analyzing of search missions; but it also undertook general RCM work and powerfully con-

SECRET

tributed to the training of RCM personnel and modifications of RCM equipment. Until a large RCM program was established in the Fifteenth Air Force, the Sixteenth Reconnaissance Squadron remained the center of all RCM activities in MTO.

Ever since the beginning of search activities in MTO, civilian technical observers from the Radio Research Laboratory of Harvard were attached to the squadron. Their presence was found extremely useful in bringing back to the home laboratory observational considerations for the improvement of the search equipment. These technical observers contributed substantially to the success of the RCM program by assisting the Army units involved in the installation, planning, and use of the RCM equipment.

Most of the personnel dealing with RCM problems all over the MTO, but especially in the Air Forces and in the Air Service Command, were originally trained in the Sixteenth Squadron.

In March 1944, the first direction finder was installed in a plane of the squadron and flown on a mission. The results obtained were immediately very good. More direction finders were ordered and later obtained. The work of the reconnaissance squadron was supplemented by ground listening stations, both British and American, and it can be stated that from the summer of 1944 on the combined results of all the investigational outfits contributed to present an almost complete and coordinated picture of the enemy radar situation.

Of the ground stations, one was an American unit located in Corsica, known by the code name Beaver III, about which more will be said, the other two were British Noise Investigation Bureau listening stations, one of them located in Corsica and the other one in the eastern part of Italy. The two British listening stations were moved, after the invasion of southern France, to cover the Balkans and the northern part of the front, which had by that time moved around Bologna.

A highly accurate DF and search ground station, called Ping Pong, built and operated by the British, was moved from England, where it had been used before the invasion of Normandy, to Corsica, in August, and later to eastern Italy.

With the beginning of a full-scale offensive RCM program within the 15th Air Force, two other sources of information became available. Operational bombers were equipped with search receivers and flown with trained personnel to watch for the enemy reaction to Allied jamming and to investigate the enemy frequency distribution near the target areas. It must be noted in this connection that the work of the Ferrets and of the ground listening stations was by necessity limited to the investigation of early-warning and coast-watcher stations and that the gun-laying sets were usually beyond the range of investigational flight and of the ground receivers.

The number of receivers available for this work was limited and only in August 1944 did the number of receivers available to the Fifteenth Air Force reach eight. Some of these receivers were used for search and later some for spot jamming. There were, therefore, enough to maintain the necessary program. In August, two groups were flying one or two aircraft equipped with search sets. The Twelfth Air Force also began to fly search receivers in August to check how important a threat enemy radar was in tactical operations.

Beginning in September 1944, the type of jamming employed in the operational aircraft required the use of a receiver for the purpose of "setting on" the jammer on the frequency of the enemy radar. The operators flying these spot-jamming aircraft were requested to keep a log of all the signals they heard. These logs supplemented the information obtained by the search receivers flown for the sole purpose of radar search in the operational bombers and contributed to the knowledge of the enemy frequency distribution. In addition to this, special recording receivers manufactured by the British were used. These receivers were known by the code name of Bagful. The Bagful tapes were used and analyzed periodically and the results obtained were coordinated with the results of the search missions and with the logs of spot-jamming operators. For instance, on two missions of October 1944, the tapes of the Bagful receivers indicated 25 signals track-

ing the formation and on another mission, also in October 1944, 23 sets appeared to track the formation on the bombing run. The results of the analysis of these tapes were very useful in order to impress upon the spot-jamming operators the importance of a proper spot-jamming technique. They were, of course, also employed to determine the extent of the jamming coverage that a formation would require on a heavily defended target.

In July 1944 the first microwave receiver was flown operationally. Repeated missions did not disclose any definite signal which could not be traced to friendly sources.

A means of defense against our jamming was to increase the spread of the operating frequencies of the enemy radar sets. Alerted by the jamming operations, the Germans took this obvious step. Search receivers, logs of spot-jamming operators, and Bagful tapes revealed during the summer of 1944 a large increase in the number of enemy signals between 510 and 550 mc. During the months of March and April 1945, the same sources revealed another frequency band used by the enemy around 450 to 460 mc. These results had also been found a short time before in ETO. Although this spread of frequency made the problem of a proper planning of RCM operations more difficult, the availability of a large number of jamming sets and of improved Chaff which arrived in the theater during the fall of 1944 permitted successive expansions of the program which enabled the Air Forces to cope at least partially with the new threats.

In the early months of 1944 another program was started to search for enemy communications signals by flying German-speaking operators in operational aircraft equipped with communication receivers. In April 1944, this type of operation was being conducted by one group. The information obtained was found useful by all of the intelligence agencies charged with the study of the enemy order of battle and determination of the enemy fighter reaction. Steps were taken, therefore, to expand the program by ordering more equipment and by training more German-speaking personnel. During the month of July 1944, about 55 Radio-Telephone [RT] monitoring sorties were flown. The number of communication intercept sorties increased steadily until, at the end of World War II, about 25 sets were installed in bombardment aircraft and about 150 monitoring sorties were flown every month. Beginning in the month of February 1945, about 50 per cent of the sorties carried disk recorders, but, owing to the strategic situation on the Italian front, many of these sorties did not intercept any enemy traffic at all.

14.6.2 Flak Countermeasures

CARPET

Definite information that enemy radar was used during daylight operations was gathered during the middle of 1943. Fortunately, a limited number of jamming sets designed to meet RAF needs was available to the USAAF.

The first plan for the employment of these sets in MTO was made before the invasion of Sicily, which took place in July 1943. Thirty-five B-17 aircraft were scheduled to jam the enemy EW systems on the approaches to Sicily; each aircraft was scheduled to carry one Mandrel, to jam EW sets, and one Carpet, to jam GL sets. Only four of these jamming aircraft arrived in time for the operation and flew the mission as planned. Another offensive RCM operation was planned on September 8, 1943, to cover the landing of airborne troops around Rome at the time of the Italian surrender. This radar screen was planned to consist of 14 aircraft carrying two Mandrels each, plus six aircraft carrying two Carpets each. As is well known, the operation was cancelled, but the six bombers of the screen equipped with two Carpets were assigned to the 97th Bomb Group, which was part of a strategic bombing air force and became the first operational bomb group equipped with RCM. At the beginning of the month of November 1943, 14 aircraft were equipped with Carpets; some of them had only one Carpet per aircraft. At that time, the North African Strategic Air Forces began to operate in southern Germany, and the losses from enemy flak became larger. The need for countermeasures against radar-controlled flak was therefore keenly felt.

SECRET

The first results obtained from flying Carpets in the 97th Bomb Group were highly satisfactory; the crews were very enthusiastic about the results. After the success of these early operations, a large-scale RCM program was formulated within the Fifteenth Air Force and the first requisition for a large number of jamming sets was placed. At the same time, a training program was started in the 16th Reconnaissance Squadron to prepare the installation teams and train officers in the handling of RCM sets. However, the amount of equipment which became available during a good part of 1944 was not sufficient to expand the RCM program greatly. For instance, it was necessary to wait until March 1944 before the first shipment of 40 supplementary Carpet transmitters arrived in the theater. In the belief, however, that the necessary quantity of RCM equipment would arrive in time, the training of installation teams continued; unfortunately, these hopes were to remain unfulfilled until the fall of 1944.

During the spring and summer of 1944, the shortage of equipment prevented the planned expansion of the installation of electronic RCM equipment. This was very important because at the same time the enemy flak was becoming more and more dangerous and the enemy, alerted by the jamming, had begun to spread his frequency band. With the limited number of sets available, even in the groups equipped with them no satisfactory barrage could be planned to cover the whole enemy band. In August 1944, it was decided to use the Carpet jammers with greater efficiency by equipping a few aircraft with three transmitters and one receiver each, with a spot-jamming operator flying in the aircraft who would listen to the enemy signals and tune the transmitter to them. This first spot-jamming effort appeared very successful and encouraged the 15th Air Force to request a large amount of RCM to make it possible not only to expand the barrage jamming already planned but also to add further spot-jamming aircraft in the group.

The situation as it existed in the month of October 1944 can be summarized by saying that of 21 groups, 6 had barrage installations, 3 had a few spot-jamming installations, and only one-third of the Air Forces had any electronic RCM at all.

The month of October can be considered a turning point in the availability of Carpet equipment. During that month, Carpets arrived in large quantity, and installation was started in 15 groups. Schools were started to train new installation teams because the teams trained in the early part of the year were no longer available. The work of installation expanded rapidly. Moving vans were established to go from group to group to explain RCM, train personnel, and install equipment. In the early days of November 1944, the return of an observer from a trip to England brought to the 15th Air Force a great deal of information on the RCM program of the 8th Air Force. The importance of dual barrage installations (each aircraft carrying two Carpets instead of one, pretuned on the ground), to cope with the increased spread in the enemy frequency band and the small formations flown, was recognized and definite steps were taken to bring the MTO program to coincide more or less with the similar program carried on in the ETO. However, the lack of military and civilian personnel made it imperative to complete first the single barrage (one Carpet per aircraft) and the spot-jamming programs which were well under way and to give to the dual barrage installations a lower priority. It can be said that, as a result of the delay in the shipping of sets and of the shortage of qualified personnel, the RCM program in the Mediterranean followed very much the same trend as in the ETO but was about 2 to 3 months behind. As in ETO, the program for the ultimate solution, formulated during November and completed just at the end of World War II in May 1945, called for ten spot-jamming aircraft per group, with all the other aircraft in the group carrying barrage with dual installations (i.e., two jamming transmitters per aircraft, pretuned on the ground). The months of January, February, and March 1945 saw the RCM program in the Fifteenth Air Force progressing at great speed.

Personnel, both civilian and military, made periodic trips to all the groups, giving information to all personnel, from generals down, on

the capabilities and limitations of RCM. The number of aircraft equipped increased steadily. In February, about 600 aircraft had either single or dual barrage, and 100 aircraft had spot jamming. February 1945 was the first month in the history of the Fifteenth Air Force when every group had some kind of electronic jamming. From that time on, the number of dual barrage installations increased, and, of course, the number of single barrage installations decreased, so that by the middle of April there were about 624 aircraft with dual barrage installations, and 163 with single barrage installations. The spot-jamming program had also been practically completed. Two hundred aircraft were equipped with spot-jamming transmitters and the necessary receivers; they were distributed among the groups on the basis of eight to ten spot-jamming aircraft per group. It might be noted here that the new jamming transmitter APT-5 was used in many of the spot-jamming installations. Altogether, more than 100 APT-5's had been installed.

It must be noted that the Fifteenth Air Force used a type of frequency distribution in its barrage which was substantially different from the one used in ETO. Formations flown consisted usually of boxes containing six or seven aircraft each. Two boxes made an attack unit. Two attack units made a group. In days of maximum effort, a group actually consisted of two attack units of three boxes, instead of two attack units of two boxes each used in days of normal effort. In any case, both in the days of normal effort and in the days of maximum effort, the distribution of barrage frequencies was such that one box had its transmitters tuned to all the odd frequencies of the enemy



FIGURE 4. Radio Research Laboratory technical observer instructing flight personnel of the Fifteenth Air Force in the offensive use of radar countermeasures.

SECRET

h-f band, and another box had the transmitters tuned to all the odd frequencies of the enemy low band. The third box had the even frequencies of the high band, the fourth box had the even frequencies of the low band. In such a way, if all the boxes flew close enough together, most of the enemy band was barraged. If only two boxes flew together, the whole enemy frequency band was still covered but with a much thinner jamming.

In January 1945, the needs of MTO, with the difficulties encountered in this theater in the installation and operation of the very large RCM program, were recognized by the authorities in the United States and steps were taken to improve the situation. The cooperation between ETO and MTO was improved by promoting exchange of visits between ETO and MTO civilian and military personnel. Three members of the ABL, which had been assisting the 8th Air Force, were sent to the Mediterranean to help the program there.

Beginning in the summer of 1944, information was transmitted between the two theaters and the United States by means of teletype conferences. Problems were discussed informally and solutions common to the two theaters were suggested. However, the lack of a coordinated laboratory in the MTO, like the one established in England, had a harmful effect on the speed of the RCM work. The limited personnel available was thoroughly occupied with the day by day problems of installation, operation, and maintenance; consequently, the amount of activity devoted to modifications and changes in the equipment that operational experience had proved to be necessary was very limited.

The RCM program in the Fifteenth Air Force, as the RCM program in all the other air forces organized during World War II, suffered because of the fact that RCM installations had to be handled in a way different from that in which signal equipment of a standard nature was dealt with. Because of supply difficulties, the number of electronic jamming sets available to the Fifteenth Air Force in the period between January 1944 and October 1944 was insufficient to keep the necessary large-scale program going. This was indeed unfortunate because that period was a very important one in the history of the Air Forces.

When RCM equipment became available, the problem of installation was a very serious one. Service Command personnel took care of the major part of the work. However, trained personnel were not available in sufficient quantity in the theater, and personnel had to be trained. This training of installation teams, which in the early part of 1944 had been done by the RCM Sixteenth Reconnaissance Squadron, was in the fall and winter of 1944 handled by a Service Command Depot which became the center of all the RCM activities. Installations involving large quantities of equipment were made in the groups, but the Air Depot prepared all the necessary kits. In addition, civilian technical observers from the Radio Research Laboratory of Harvard took a leading role at this time in organizing the different parts of the program. Mobile vans were going from group to group to help in the installation and to give a series of lectures to all the personnel. Because of the necessity of getting in touch with all the personnel, the same lecture had to be repeated two or three times. Different lectures were given to staff officers, combat crews, and RCM and signal personnel.

CHAFF

The very first use of Chaff in the 15th Air Force was made about February 1944. The quantity used, however, was small because of lack of supply. Not until March 1944 did a substantial quantity arrive.

Use of Chaff in appreciable quantity began, therefore, at the beginning of April 1944. Chaff was received with enthusiasm by the crews and the personnel of the Fifteenth Air Force. The effectiveness of Chaff at the beginning was exceedingly good, and the crews reported flak hitting the Chaff trails and not the bomber formation. After the first use of Chaff in April 1944, the Chaff supplies were never very large, but they never reached as low a point as the supplies of RCM electronic equipment.

In the first months, the amount of Chaff dropped was of the order of 12 units a minute, substantially lower than the figure used later. Because of the limited amount of Chaff avail-

SECRET

able, Chaff was not dispensed by all the formations but only by those flying in the leading positions.

It was clear that the amount of Chaff protection given to the leading formation was rather small as compared to the amount of protection available to formations flying within or near the Chaff trail. It was, therefore, decided to attempt a type of operation in which Chaff was dispensed ahead of the leading formation by means of fighters. Since *Chaff dispensers* for fighters were not available at that time, special *Chaff bombs* were prepared. Fighters equipped with these Chaff bombs flew ahead of the main formation and dropped Chaff bombs at the proper intervals up wind of the main bombing run. The effective success of Chaff in all the operations made another revision of the Chaff requirements for the Fifteenth Air Force necessary. The requirements were revised upwards to a figure of three million units a month, and an attempt was made to keep the figure of Chaff dispensed on the order of 27 units per minute per aircraft. Chaff was still used only on heavily defended targets until at least the end of September. Chaff bombs were reported very successful, with some crews seeing very wild shooting by the enemy flak batteries, with bursts often several miles from the nearest formation. At the end of August 1944, the Twelfth Air Force also began to use Chaff in B-25 and B-26 aircraft. During the months of October and November, Chaff was used by both the Twelfth and Fifteenth Air Forces in larger quantities, with more and more formations dropping Chaff.

The need for Chaff dispensers was very keenly felt and the first prototype using the *A1 Chaff dispenser* developed in the United States was flown satisfactorily. It was found, however, that changes had to be made in order to make it suitable for installations in all the aircraft of the Air Forces.

The arrival of a substantial number of A1 Chaff dispensers in January 1945 enabled the Fifteenth Air Force to begin the installation of them in its operational bombers. However, serious difficulties were encountered because of mistakes made in the United States during the assembly of the stripper gear. The help of a specialist was requested from England and the work of installation was stopped for a while. In March 1945, the arrival of the specialist from England enabled the work on Chaff dispensers to be continued. Changes were made in the dispensers and mockups prepared for all types of aircraft involved. Three hundred dispensers were installed in six groups on the basis of 50 installations every three weeks. Not only the dispenser but also the chute had to be changed both in the B-25 and in the heavy bombers. In the month of April, the work on the installation of Chaff dispensers really was going at full speed. As of April 15, 1945, more than 500 dispensers had been installed.

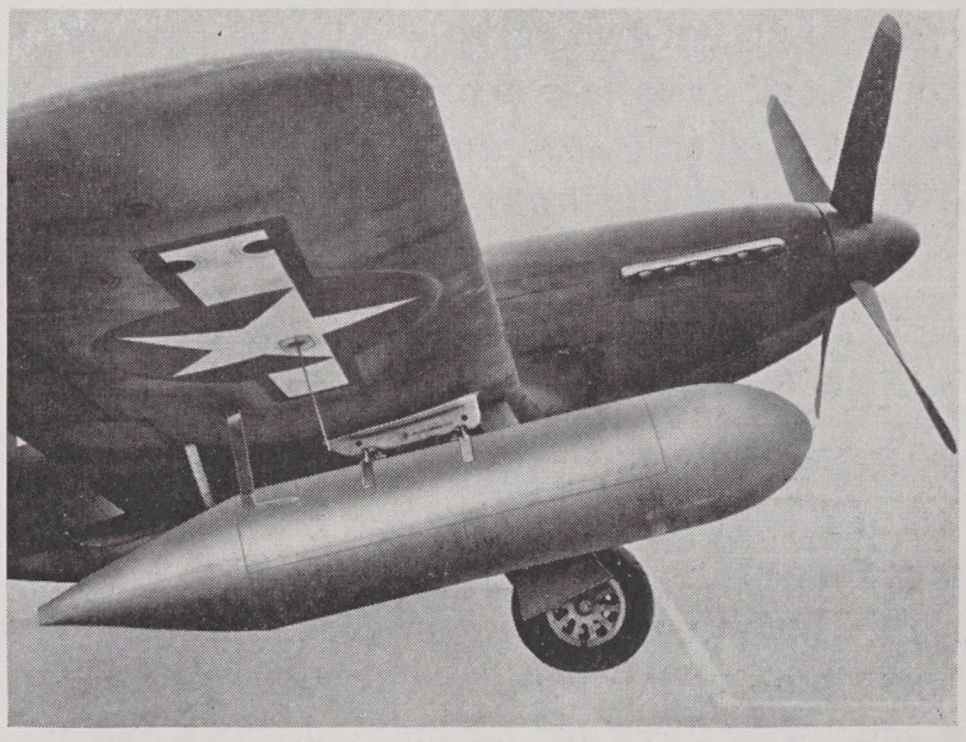


FIGURE 5. A-4 type Chaff dispenser intended for fighter installation in order that protection could be given to lead bomber formations.

The RCM program of the Twelfth Air Force was limited because of tactical considerations. The B-25's of the 57th Bomb Wing flew in such formations and principally at such altitudes that countermeasures could be considered effective only under blind bombing conditions, and thus, until the installation of their Shoran equipment in the fall of 1944, there was little in the way of RCM requirements. Looking toward the installation of blind bombing equipment, however, plans were laid to combine an effective RCM program with the blind missions, and also to get what benefit could be obtained by direct action on visual missions. The "direct action" was taken by a small lead formation. This lead formation would approach the *gun positions*, attempting to cross the target on the

SECRET

axis of attack for the following bombers, laying a Chaff trail to cover the bombers. They would then bomb the gun positions with white phosphorus bombs, with the dual aim of demoralizing or injuring gun crews and also of obscuring the visual range finders. If it was not possible to continue over the target to the gun positions, the lead group would hold the bomber axis as long as possible and then break into their own run. On visual missions, the white phosphorus was considered the primary countermeasure and Chaff secondary. On obscured missions, the Chaff was the primary countermeasure and the phosphorus secondary.

Ultimately, it was planned to install spot jammers in about 10 per cent of the aircraft, and Chaff dispensers in a larger percentage, but operations ceased before any jammer activity was initiated and only a small number of dispensers had been installed and used.

14.6.3 Fighter Countermeasures

For reasons already mentioned, the amount of RCM directed against fighters was very limited and sporadic. The British bombers based in the Mediterranean and conducting night bombing activities did use a certain amount of radar countermeasures against the enemy EW system. These countermeasures were carried on by the use of British Mandrels employed against German Freyas. A small number of other sets peculiar to the RAF were used by these Wellingtons, but no large-scale effort ever took place.

In the late part of 1943, a plan was started within the headquarters of MAAF to establish a ground jammer station in Corsica. At that time, the Germans occupied the whole coastline from a point north of Naples all the way to the Spanish border. Corsica being in the middle of the western part of the Mediterranean was in a reasonably good position to conduct ground jamming. For this reason, the authorities in the United States were requested to prepare and send to the theater a Signal Corps unit known by the code name Beaver III. When the unit was requested, no definite operational plan existed for its use. Because of its position, with reference to the enemy radar chain, no complete jamming coverage of the approaches to the enemy coastline could be guaranteed except within a distance of about 40 or 50 miles. Furthermore, jamming facilities available to the unit were such as to cover only the Freya frequency band. Observations of the signals from enemy coast-watcher stations appeared to show that these stations were also used as early warning. These reasons, coupled with the fear that jamming operations against the Freya chain might have interfered with the Allied v-h-f communication network, prevented the Beaver III unit from carrying on any continuous jamming work in support of the strategic air forces. After several delays due to the uncertainties in the organizational and operational planning setup, the unit arrived in Corsica during the month of March 1944 and completed the installation of its equipment during the first days of April. Before that time, a series of tests had been conducted at Oran to determine the limitations of jamming equipment imposed by the danger of communications interference to friendly sets.

After the unit was installed, it used its receiving and DF facilities to obtain information on the enemy radar chain, but did not conduct offensive countermeasures until D-Day in support of the invasion of southern France. Mention has already been made of the value of the search information obtained by Beaver III. It must be mentioned here that the invasion of southern France occurred at a point on the coastline very far (about 120 miles) from the island of Corsica and that therefore the jamming of the enemy radar chain was a difficult task. The details of the RCM plan for the invasion of southern France will be given in a later section, where mention will be made of the part that Beaver III played in the operation.

It might be useful to note here that the Beaver unit had attempted three times during World War II to do an effective job of ground jamming. The first time the unit was deployed against the Japanese radar in Kiska, the second time in Corsica, as previously discussed here, the third time in the Pacific Theater. In none of these three cases was any effective continuous ground jamming found to be possible, because of strategic or tactical considerations.

14.6.4 Miscellaneous

Among the miscellaneous activities carried on in support of the RCM program were the testing activities first conducted by the Sixteenth Reconnaissance Squadron and by the Fifteenth Air Force.

When Italy fell, one captured enemy GL set out of three available was left in the theater. The other two were sent to England and the United States for intelligence purposes. This set, after some work, was put into working order and was used in two series of tests carried on in 1944. The first test, during the month of March, had the purpose of testing the effectiveness of our electronic jamming. The results were quite interesting but the test was handicapped by the difficulty of obtaining a substantial number of planes to simulate a formation. Later in the year, the Fifteenth Air Force supplied the necessary number of aircraft and a series of flights was flown against the captured set in order to test the effectiveness of the Chaff-dispensing technique. For several reasons, the quantitative results were not completely satisfactory, although they were very useful to the people in charge of the planning of the RCM operation. The number of Chaff units necessary to cover a formation was determined from these tests, and this figure was used until more complete results became available from work done in the United States.

Another activity worth mentioning is one involving work to protect friendly radar sets against the jamming carried on by the enemy. During the months of April, May, and June 1944, a substantial effort was carried on by the Germans in the jamming of Allied ground sets in the Anzio beachhead and airborne aircraft-interception sets. It was very unfortunate that the lack of appreciable diversification of the frequencies of the Allied EW, GCI, and AI sets increased their jamming vulnerability. A large percentage of these sets were working at frequencies around 200 mc, so that the Germans with a few ground-based jamming transmitters tuned around that frequency managed to interfere very seriously with our operations. The jamming carried on by the Germans consisted essentially of C-W and railing jamming. Window was also used very extensively. It is important to note that jamming was so effective as to make our 200-mc GL equipment practically worthless and to make the work of our AI set very much more difficult than it had been in the past. As a consequence, there was a large decrease in the number of enemy aircraft shot down by night fighters. The GL radar position in the Anzio beachhead was greatly improved when more modern sets like the SCR-545 and SCR-584 were brought into the beachhead. A further improvement was obtained when the more modern microwave AI set was substituted for the older 200-mc Mark IV AI set used up to that time.

Before these sets became available, however, work had been requested by the radar personnel on the development of antijamming devices. These AJ devices were developed and installed by one of the civilian technical observers. Modifications were made in the radar set, the frequency band of the i-f stages was decreased, and noise limiters were installed. One of the reasons why all the GCI sets were working around the frequency of 200 mc was that no large spread of frequency was possible with the type of IFF using the G band. An effort was made to modify the IFF to allow for a spread of about 10 mc. These efforts were successful, but no large-scale work was done because the new sets became available about that time.

14.6.5 The Effectiveness of the RCM Program

After the defeat of Rumania by the Russian troops, a technical mission was sent to Rumania about August 1944 to analyze the flak defenses of the Rumanian targets which had been hit by the Fifteenth Air Force. The results obtained by these investigation teams were of the highest interest. Up to that time, the amount of Chaff used by the Fifteenth Air Force had not been very large but had been reasonably satisfactory; the amount of electronic RCM used, however, had been extremely limited. Despite this fact, the reports that the intelligence officers brought back were of such a nature as to give the impression that RCM had been effective

beyond the most optimistic hopes. The Rumanian officers interrogated gave tremendous credit to RCM in decreasing the amount of flak losses suffered by the Fifteenth Air Force. They said, for instance, that RCM was not only useful in days when the overcast prevented the optical range finders from operating, but also on the days in which the visibility was good, because the smoke screens used by the defenders made the use of radar very important. They added that RCM had put these radars out of action many times. In listing their suggestions for the improvement of the American raids for the purpose of decreasing their flak risk, RCM had first priority. A measure of the effectiveness of the enemy flak, or, better, a measure of its ineffectiveness, can be given by the figures of the number of shells shot by all the batteries of Ploesti, the second most heavily defended target in the world. The number of planes shot down and the ammunition expended was such that about 25,000 rounds were found to be necessary to shoot down one plane. These figures should be compared with the figure of about 350 rounds per bird used by the American and British ack-ack batteries to shoot down buzz bombs.

After V-E Day, a mission was sent to northern Italy for the purpose of studying the flak situation there and, if possible, to evaluate the success of our countermeasures against their radar gun-laying system (see Figure 6). The following abstract from the report written on the subject gives a summary of the results obtained.

It was perfectly clear that, at least in the Italian Theater, German officers in staff positions had very little respect for their gun-laying radar. The reason for this was twofold.

1. The educational program was limited because of the secrecy restrictions.

2. The interference by Allied countermeasures seriously affected the radars' operation.

An example of the poor educational program is the fact that several flak battery commanders believed that their radar had attracted Allied bombers and bombs, and had sometimes ordered it turned off.

An accurate opinion on the effect of Allied countermeasures could only be obtained from the junior officers in charge of equipment. However, in spite of the limited knowledge possessed by each officer, every one of them voluntarily mentioned the effect of RCM, and knew the names and use of several of their anti-jamming devices. Of course their opinions varied on the effectiveness of the interference, and in general, varied with the rank of the officer. A flak battalion commander would generally say that Allied interference was often encountered, but that their anti-jamming devices, which he would describe, were usually able to counteract any form of interference. And in cases where radar was jammed,—it didn't really matter because they always depended on the optical system.

The junior officers directly responsible for the operation of the batteries had a somewhat different view. These officers believed that the small Wurzburg could be more accurate than the optical system, if it were not interfered with by jamming. However, the Allied countermeasures had made this gun-laying radar of little use against four-engine bombers. The continuous interference from Chaff and electronic jamming had not given the radar a chance. Opinions were divided on the most effective form, but generally favored the Chaff operation. In most cases, they seemed to be able to sidestep the electronic jamming, but often it was only temporary. Frequently it was possible to eliminate the Chaff interference, but occasionally the concentration was so high that Wurzlaus had little effect.

One of the most startling impressions came from the young German officers who felt that the high command in general was too conservative and backward. One lieutenant, a young physicist who knew of the world's great scientists and their work said, "The war turned with our defeat at Stalingrad and the use of Rotterdam (British H2S)."

Frank opinions of the junior officers were never given in the presence of their seniors. However, one major, a battalion commander, was amazed that the Allied scientists were so young, and remarked, "We were fighting against children,—and we were beaten."



FIGURE 6. Radio Research Laboratory technical observers and Fifteenth Army Air Force officers interrogating German radar and flak officers in Italy.

The Allied use of RCM, its effects, and the German

SECRET

anti-jamming devices was one subject of which all channels of command were well aware. The repeated failure of their gun-laying radar under Allied RCM, and a lack of education produced rumors on the equipment and had caused it to be considered, even at the batteries, as a secondary means of flak control.

During the last six or eight months, the intensity of the Allied jamming had increased until both radar operators and technical personnel believed "the game was about up." Chaff concentrations were reported to have placed the noise level too high for Wurzlaus operation, and the use of Carpet had forced the frequency of the Wurzburgs to the practical limits. The general opinion was that Chaff generally had more effect than Carpet. They definitely agreed that the use of both forms of interference was still advantageous on a clear day.

14.7 THE OPERATIONAL USE OF RCM IN THE ETO

14.7.1 Search and Investigation

The RCM program of the U. S. Armed Forces in the ETO began in the summer of 1942 when the Eighth Air Force began to be interested in the problem of enemy radar. Because of the lack of more suitable search equipment, an investigation of the use of radar by the enemy during Eighth Air Force attacks was commenced with a British warning receiver called Boozer, which was installed in a heavy bomber of the attacking formation in order to determine where the radar signals could be heard during the attack. The results of this search immediately indicated that, as expected, enemy radar was being used during these daylight attacks. Thus still further interest was aroused in using Carpet to jam the enemy radar.

The Carpet program was started by the Eighth Air Force on October 8, 1943. The initial information on the Wurzburg frequency band was obtained from the British, and on the first mission Carpets were tuned at intervals of 1 mc over the frequency band of 550 to 570 mc. Inasmuch as the Carpet program was based on jamming the frequency band where the enemy operated, an obvious antijamming measure by the enemy was to spread his radar frequencies; the wider the frequency spread, the more difficult it would be to cover it adequately, particularly with a small number of equipments. In order to keep track of the spread of the enemy's frequencies, it was necessary to maintain throughout World War II a continuous investigational program with airborne search receivers.

In October 1943, ABL-15 provided the Eighth Air Force with a few handmade models of a Blinker search receiver, a receiver which required an operator and which had a panoramic type presentation. To determine the enemy frequency, the receiver was first used to search in the German Wurzburg band from 450 to 650 mc. A Blinker search receiver was first flown on November 15th, and after this time search receivers were flown on almost all missions conducted by the Eighth Air Force. The first results from the use of this equipment showed that the enemy frequency band had spread to possibly 524 to 597 mc. It was difficult to make an accurate statistical study of the frequency distribution of flak radar by means of this equipment, since no means other than aural was provided to differentiate between the large and small Wurzburgs which were believed to be used for GCI and flak control respectively.

Search operations were continually extended after these initial operations and were a very important part of the RCM program. As improved equipment became available, more and better information was obtained concerning the enemy's operation. The Carpet and Chaff programs were continually modified as a result of these search operations.

A British recording receiver known as Bagful was first tested operationally in January 1944 by the Eighth Air Force. The distribution of frequencies used by enemy radar equipments was thus recorded and careful analysis was made of the results. Unfortunately, Bagful did not distinguish between the small and large Wurzburgs, which had different pulse-repetition frequencies [prf], and, therefore, complete reliance could not be put on this equipment for recording the frequency spread.

In January 1944, the use of the Blinker receiver was extended to the 250 to 450-mc band in an attempt to determine whether dangerous enemy radar signals existed in that region. Some work was carried out by ABL-15 on the design of a prf meter for the Blinker receivers,

SECRET

although this work was not too successful since the equipment failed to operate properly when more than one radar was on the same frequency at the same time, which often was the case.

Since the flak losses of the Ninth Air Force were very low compared with those of the Eighth, considerably less priority existed on RCM in that command, but in the early part of 1944 a Blinker search receiver was installed in a B-26 aircraft and a search program carried on for several months in an attempt to determine whether the RCM problems of this command were similar to those of the Eighth.

The Eighth Air Force commenced flying radar screens in the beginning of 1944. The purpose of the screens was to prevent the enemy EW radar from detecting the approach of bomber formations for as long as possible. In connection with these screening missions, a number of search programs were conducted in order to determine how the enemy EW radar was used during these attacks. The German EW radar system became very complex before the end of World War II, and much of the information concerning the subject was obtained by the British through their ground listening stations and airborne intercepts.

The Eighth Air Force commenced flying AN/APA-17 radar DF equipment in July 1944. It was hoped that this equipment would aid in the problem of locating and identifying specific ground radar installations, and that by a study of the operational procedures of a given station, considerable information of value to the RCM program could be obtained. Because of the high density of German radar, it was very difficult for an operator to follow a single radar station for a long period of time. Direction-finding fixes which supposedly were made on one station were often found to have been taken on several ground radars. An interesting use of the APA-17 equipment developed during these operations. Operators found that by noting the direction of large concentrations of radar stations, it appeared to be possible to predict the location of flak areas, and on several occasions when the formations became lost over enemy territory, it appeared feasible to use the equipment as an aid to avoiding regions of heavy flak.

An ever-present cause for fear in the Air Forces RCM program was that the enemy would resort to entirely new radar equipments for flak control. One of the obvious steps in this direction would have been the use of microwaves, and it was considered important for this reason to maintain a search program for new enemy signals outside of the usual range. In June 1944, an APR-5 microwave search receiver was installed in an Eighth Air Force B-17, and it was occasionally flown over enemy territory after this time. In February 1945, the APR-7 microwave search receiver was installed and flown by the Eighth Air Force in a P-38 aircraft, and later in the main bomber force, in order to search for the use of microwave radar by the enemy. The results of these microwave searches were not significant and although a number of signals which did not appear to come from Allied equipment were recorded, positive identification was difficult to make.

Toward the end of World War II, the APA-17 direction-finding equipment was fitted with a microwave head for use in connection with this search. Because of the many unidentified 10-cm intercepts which had been made, it was essential that means be provided, such as by DF equipment, for positive identification of the signal as enemy or friendly. An operator training setup was constructed in connection with the program, but the progress of the war was such that it did not come into use.

Because of the scarcity of production receivers for the spot-jamming program, investigations were started to try to find alternative equipment for the purpose. In addition to the use made of the small number of Blinker equipments mentioned previously, a few APR-1 receivers were obtained from the U. S. Navy and used. It was found that the British Carpet II, with suitable modifications, could be employed as a receiver, and a number were so used by the Eighth Air Force.

The search for a suitable and available receiver for spot jamming and the improbability of obtaining such receivers in the near future from the United States led to the design by ABL of a simple autodyne receiver. Approximately 500 of these receivers were constructed at the Air Force Base Air Depot from the

SECRET

laboratory design. Personnel of the laboratory aided with the testing and supervision of this program and eventually with the installation problems. The equipment proved to be useful and many sets saw actual operational service. However, since the equipment was inferior in operation to the APR-4 receiver, it was replaced when APR-4's became available in the fall and winter of 1944.

The arrival of APR-4 search receivers in small quantities in September 1944 permitted their use in the search aircraft of the Eighth Air Force, replacing Blinker receivers. ABL-15 built a number of audio oscillators for use with these receivers because of the shortage of much equipment in the theater. The audio oscillators were used with the APR-4 and whatever oscilloscopes could be obtained for measuring the characteristics of enemy signals. These oscillators were designed around the American SCR-274N command receiver, using some of the components, and a number of these oscillators were made at the Base Air Depot from the ABL-15 design.

In the beginning of 1944, the Eighth Air Force commenced a program of enemy v-h-f intercepts which carried through until the end of World War II and undoubtedly was of considerable value in obtaining much needed information from the enemy ground and airborne fighter traffic. S-27 and later German Fuge 16 receivers and German-speaking operators were carried in the bomber formation. Some attempts were made to use magnetic and disk-type recorders in this program, but these were not thought to be particularly useful. The results of all of these investigations were immediately transmitted to the British Intelligence Organization and from them directly to the Eighth Air Force, which made use of them in operational planning.

14.7.2 Flak Countermeasures

CARPET

The first shipments of Carpets arrived in the theater in September 1943 and were installed in two bomb groups of the Eighth Air Force. These jammers were first used on October 8, 1943, by 38 of the 42 aircraft of the 388th and 96th Groups in an attack on Bremen. Initial reports indicated considerable success in the reduction of flak losses and as a result the Carpet program received great impetus. From the commencement of the program at this time up to October 1944, when adequate deliveries of equipment made extensive use of Carpet possible, only about 9 per cent of the Air Forces was equipped with Carpets. Sufficient additional equipments were received after the initial quantities to keep up with the increase in the size of the Air Forces and to replace losses, so this percentage was maintained for about a year. The Eighth Air Force Carpet program from October 1943 through April 1945 is given in Table 2.

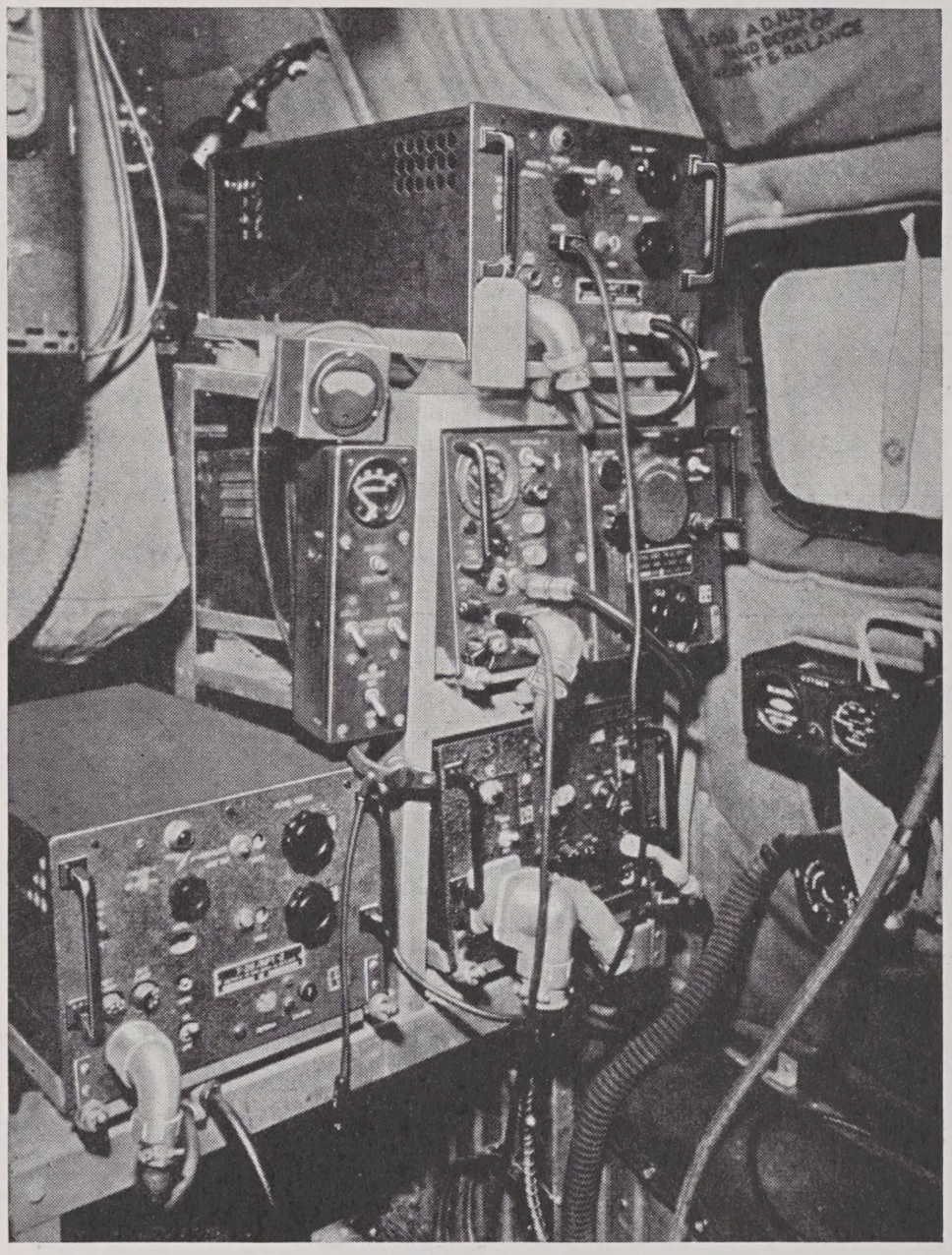


FIGURE 7. ETO spot-jamming installation in a B-24. Shown from top to bottom are 1 AN/APT-2, 1 AN/APR-4, 1 AN/APQ-9, and to the left, 1 AN/APT-2.

With the instigation of even so small a Carpet program in the last months of 1943, the Germans attempted to counter the use of electronic jammers by spreading their flak radar frequen-

cies. With only a very few Carpets available, it was important that equipment be used to maximum advantage. For this reason, consideration was given to modifying Carpet so that an operator could tune it rapidly, by means of a monitoring receiver, to the enemy radar frequency. By this means, if 100 per cent effective operation were possible, the number of jammers required would be equal to the maximum number of enemy radar stations in use against the formation at any one time, which would be only a fraction of the number of barrage jammers needed. ABL-15 commenced work in December 1943 on the use of Carpet as a manually tuned spot jammer for both the 8th and 9th Air Forces. A standard Carpet I transmitter was modified so as to make it possible to tune the equipment rapidly over a band 75 to 100 mc wide at any frequency in its range of 450 to 710 mc. This equipment was first flown in May 1944 by the 44th Group of the Second Division, 8th Air Force, and, although this program was extended to three other groups in August, it was not until the winter of 1944-1945 that the spot-jamming program was complete.

TABLE 2. Eighth Air Force Carpet program.

Date	Number groups equipped Barrage	Spot	Total number sets installed Barrage	Spot	Comments
1943					
Oct 4	2	0	68		
1944					
Feb 16			125		
March			177		101 Sets lost since start of program.
April 1	4		124		
May 1	4		148		
May 15	6		223		
May 21	6	1		6	Spot jamming started.
June 15	6		215	6	
July 15	6		165	31	
Aug 1	6	4	184	65	
Sept 10	6	4	141	62	
Oct 10	6	4	120	81	
Nov. 1	10	11	1,342	126	
Nov 20	28	13	2,746	147	Dual Carpet barrage in all aircraft except Pathfinder practically completed.
Dec 10	38		3,098	253	Spot-jamming installations starting in all divisions on basis of 12 aircraft equipped per group.
Dec 31	40		3,460	507	
1945					
Feb 1	40			1,254	Spot installations essentially complete.
April 1	40	40	2,608	1,260	Triple barrage installations commencing.

Eventually this equipment was used in about two planes per squadron of 12 aircraft, with one operator and three jammers per spot jammer-equipped aircraft.

In January 1944, both the 8th and 9th Air Forces requested the laboratory to test the British automatic-selective jammer Carpet II, with a view toward using it in their bomber formations. The British Carpet II was an equipment which automatically hunted for the frequency of the enemy radar station, then locked on it, and jammed for a predetermined length of time, functioning, in effect, as an automatic spot jammer without an operator. However, since the power output of this jammer was only about ½ w, it was determined that the number of equipments which would be required adequately to jam the German small Wurzburgs would be excessive.

The training of operators was an important part of the spot-jamming program, and in June 1944 the Eighth Air Force assigned certain aircraft of the 36th Squadron to be equipped with training installations of spot-jamming equipment; in addition, bench spot-jamming setups equipped with signal generators simulating a small Wurzburg aided in the training program. This training program reached considerable magnitude when the installation of spot-jamming equipment in all the groups of the Eighth Air Force was commenced in November 1944.

As is indicated in Table 2, the Carpet program was very small during the period when it was needed very badly. However, the Carpet program reached full proportions for 6 months of the 8th Air Force's 31 months of operations, and these 6 months were the months when the attacks on German targets were the heaviest. The following considerations, which were determined at the time when the Carpet program was reaching practically full strength, resulted in a decision to establish the RCM program of the Eighth Air Force on a basis of barrage and spot jamming, each supplementing the other as effectively as possible.

1. The number of radars with which the enemy batteries were equipped was about one radar to each ten guns. On the heavily defended targets as many as 250 to 300 guns could en-

gage a formation and up to 15 radars could be tracking at the same time.

2. By means of an investigational program, the density of enemy sets at all frequencies was determined. Barrage jamming was used to cover the region where the density was highest. In a 12-aircraft squadron with Carpets spaced 1½ to 2 mc (this applies to APQ-9), a maximum of 48 mc could be covered. This was definitely not enough to jam the whole enemy band; furthermore, for several reasons RCM sets had to be taken out of H2X aircraft, with a consequent reduction in the number of megacycles covered.

3. Another element to be taken into account was the general trend toward the reduction to nine or ten aircraft per squadron; by the end of World War II, practically all divisions were flying eight RCM aircraft per squadron.

The use of spot jammers alone would have been difficult since, as stated above, the number of radars looking at the formation at a given time might reach as many as 15. This would have required five or more spot-jamming aircraft per squadron, which would have presented serious problems in obtaining operators and receivers. Furthermore, in the region where barrage was used it was probably more effective since, when the barrage jammers were carefully tuned to their assigned frequency, a small rapid frequency shift on the part of the enemy radar would not result, as it might in the case of spot jamming, in the avoidance of the jamming for a short period. Actually, the ideal jamming system was a barrage; however, the impossibility of covering all of the enemy frequencies with barrage jamming eventually led to the adoption of spot and barrage jamming together.

In conclusion, after several discussions in which all of the above factors were examined, a decision was reached to have two aircraft in each squadron carry three spot-jammer transmitters, and to equip all the other non-PFF (Pathfinder) aircraft with dual barrage installations.

The band covered by the barrage varied from time to time depending upon the results obtained by investigation of the enemy frequency distribution. For quite a few months starting in October 1944, each group of the Air Forces had two squadrons barraging the high band from about 550 to 580 mc and one squadron barraging the so-called low band from about 520 to 550 mc. This distribution was changed when the enemy transferred a large proportion of its sets towards lower frequencies around 460 mc and was further changed when simple considerations showed it was better to have all the squadrons of a group covering the same band. A situation was reached at the end in which each squadron of a group jammed the same band but different groups barraged different bands; the spot-jamming operators were charged with the task of jamming all signals which appeared outside of the frequency bands being barraged.

With the availability of sufficient Carpet III's, a program was started in November 1944, by the 8th Air Force, to replace all Carpet I's with Carpet III's. An acute shortage of tubes for this transmitter developed as a result of their short life and the difficulty of obtaining spares, and ABL-15 conducted a thorough investigation into the causes of the tube failures.

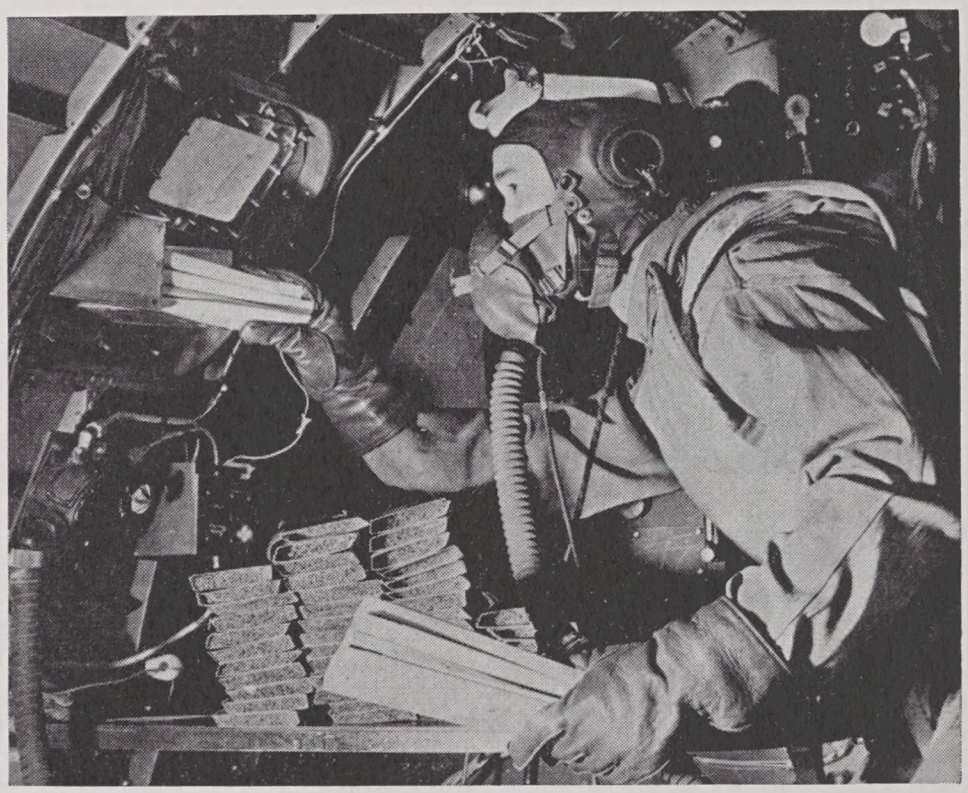


FIGURE 8. B-17 crew member dispensing an early form of Chaff from chute in the radio room.

Although large numbers of APT-5's were never received in the theater, a small number, built on a crash program, were put into use in the 8th Air Force as spot jammers. Plans were made to replace, eventually, all Carpet I and III barrage and spot jammers with APT-5's, but

SECRET

World War II ended just as large shipments were arriving.

CHAFF

The Eighth Air Force first used Chaff on December 20, 1943, about 2 months after Carpet was used for the first time. After V-E Day, it was found that the Germans had considered the use of a similar system in the summer of 1940, long before the first use by the Allies in 1943, but had kept it secret for security reasons from everyone except the high-level personnel. The success of Chaff was, therefore, very great because of the element of surprise.

When the American Air Forces began to use it, the supply was not sufficient for large-scale operations and British supplies had to be employed for a considerable period. Perhaps because of an erroneous concept of the accuracy of the navigation of the bomber formations, the requirements transmitted to the United States were far below the actual quantity necessary for a complete and effective program. In effect, Chaff plans and Chaff requirements were based on its use only by lead formations and not by all aircraft, as was later done. In Table 3 are given the quantities and types of Window which were used by the Eighth Air Force.

Even in the summer of 1944 when practically all aircraft started dropping Chaff, the tactics remained stereotyped and it became standard practice to begin a few miles after the initial point [IP] and stop when leaving the target area. Fortunately, however, with universal use of Chaff, operating personnel gradually became accustomed to thinking of Chaff as another tactic available to them. Army and civilian technical personnel contributed greatly to the understanding of Chaff in the headquarters and operational units. As a result of the increasing familiarity of Chaff as a weapon, the methods of employing Chaff increased in variety and in number beyond the standard dropping technique already outlined (which involves dropping about 24 units a minute from each aircraft in the target area). Mosquito aircraft were equipped with Chaff dispensers and were flown

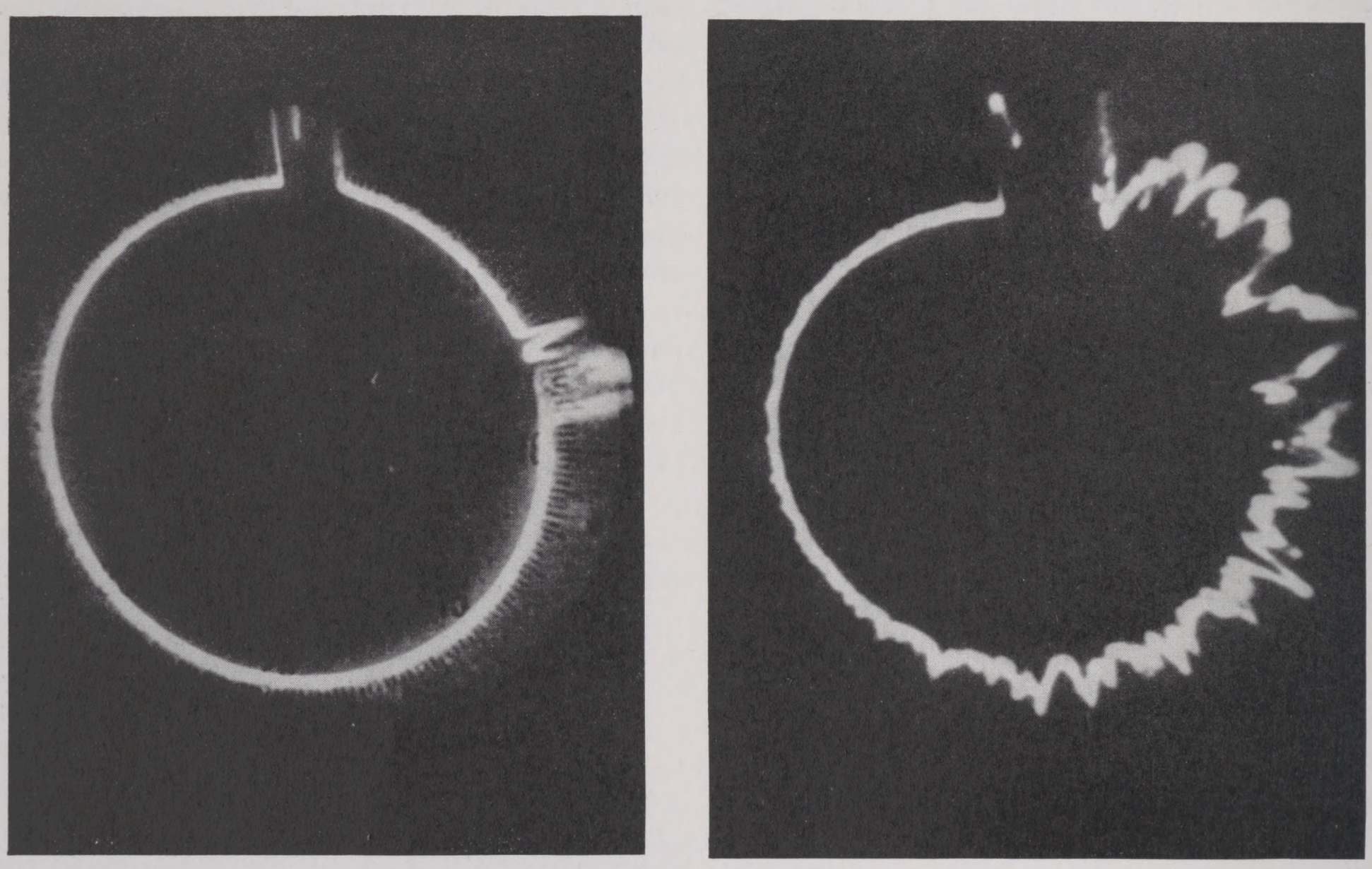


FIGURE 9. A captured German photograph showing the appearance of a heavily infested Window area as contrasted with normal appearance of the A scope on a Wurzburg radar.

ahead of the main formation to dispense Chaff before the bombers arrived. Special bomber forces were equipped with chutes to permit the dispensing of large quantities of Window in a short time and were sent ahead of the main formation. Fighters were equipped with Window-filled droppable flare bombs and often Chaff tactics were employed only with the general purpose of confusing the enemy with new and unexpected effects. Chaff forces were called upon one day to circle a target, dispensing Chaff, or to lay a Chaff trail along a course perpendicular to the penetration course of the main force. In other cases, a division bombing Target A would dispense Chaff up wind of Target B, which another division was going to bomb 10 min later. These and many other examples could be given of the variety of employments of Chaff.

TABLE 3. Use of Window by Eighth Air Force.

Date	Used per month	Types
1943		
Dec 20	First use	CHA3
1944		
Feb	Approximately 80,000 lb	CHA3, and British A, C, and G
Mar	250,000 lb	CHA3, A, C, G, J
Apr	519,000 lb	
May	713,000 lb	
June	1,145,000 lb	
July	1,601,000 lb	CHA3, C, F, G, J, X
Aug		CHA2, 3, 28, C, F, J, J3
Sept	5.6 million units*	CHA3, 28, F, J, X
Oct	7.2 million units	CHA3, 2, 28, 28-3, J, J3, X
Nov	6.4 million units	
Dec	6.3 million units	CHA28-3, 3, F-3, J, J3, X
1945		
Jan	5.3 million units	
Feb	8.5 million units	CHA28-3, F-3, A, X, XE
Mar	10.8 million units	CHA28-3, F-3, A, X, XE
Apr	5.9 million units	CHA28-3, F-3, A, X, XE

* Exact conversion to weight cannot be made because of the many different types of British and American Window which were used.

The time came at the end of 1944 when all the operational personnel were cognizant enough of the capabilities of the little strips of aluminum made available to them that the Headquarters Eighth Air Force decided it was advisable to leave to the subordinate division headquarters complete freedom of action in the use of this countermeasure. The amount of Chaff required increased continuously and, when tests against a Wurzburg equipped with a captured AJ device showed that it was desirable to double the amount of Chaff dropped, requirements were initiated for as many as 20,000,000 units—more than 2,000 tons—of Chaff a month. Inasmuch as World War II ended, however, no deliveries of the increased quantities were actually made, but this example is given for the purpose of contrasting it with the initial requirement made in December 1943 of 500,000 units a month.

Chaff dispensers were considered at several times as a standard item for all bombers, but it was repeatedly found that the manual dispensing method used until the end of World War II was satisfactory. However, the United States authorities had been requested to install Chaff dispensers in all replacement aircraft. Again, the end of the war prevented this request from being fulfilled.

With the definite possibility of use by the enemy of centimeter equipment and in the absence of an electronic jammer covering the centimetric band, a requirement was established in early 1945 for 1,000,000 units a month of centimeter Chaff to be kept stored as insurance against future enemy developments. Fortunately, World War II ended before the Germans were able to make use of centimeter radar on a large scale and, therefore, the centimeter Chaff was not used.

14.7.3 Fighter Countermeasures

Countermeasures against German fighters did not play nearly so large a part in the electronic warfare of World War II as flak countermeasures. Table 1 indicates that the maximum losses of all bombers to enemy fighters occurred in the period January to July 1944. However, at this time, losses to flak had climbed very considerably over the previous six-month period and, therefore, there was not so much emphasis on fighter RCM during that period as there was in the previous year when the fighter losses were many times the flak losses. Also, as mentioned previously, with the advent of the long-range fighter and a full-fledged offensive against the Luftwaffe, the whole strategy became one of welcoming combat in order to weaken the enemy. It will, therefore, be seen that the advent of the long-range fighter greatly changed the need for a countermeasures program. In 1942 and 1943 a vigorous fighter countermeas-

SECRET

ures program would probably have been very successful. However, at that time American knowledge of RCM was meager and equipment to do the job was lacking.

A project was undertaken in December 1943 to jam the German fighter communications in the frequency range 38 to 42 mc with ground-based jammers located on the eastern coast of England. Prior to this time, the RAF had undertaken a similar program and had installed 600-w f-m barrage jammers known as Ground Cigars for this purpose.

Since a single installation would have been satisfactory for both the RAF and the Eighth Air Force, steps were taken to insure British and American cooperation in this project. Studies made by ABL-15 of the existing British setup indicated that these installations were not very effective in jamming the enemy because of insufficient power. The modification of these barrage jammers was undertaken to make them suitable for spot jamming, so that they could be quickly tuned over the desired band and monitored onto the enemy signal by an operator. In addition, a very substantial improvement over the existing Ground Cigar antenna installation was made by erecting the antenna on the top of a 360-ft chain-home [CH] radar tower. Plans were made for the modification of 15 of these jammers, but the interest of the Eighth Air Force in the project decreased as the fighter problem was solved by the use of Allied long-range fighters and the program was never carried through.

In December 1943, the 8th Air Force commenced the installation of equipment to operate as an airborne radar screen to jam the German EW system. The screen was flown early in 1944 for a number of months, although the usefulness of this effort was rather doubtful. The aircraft carried Carpet transmitters to jam the Wurzburgs and Mandrels to cover the Hoardings and Freyas. Ordinarily the screen was used during bomber assembly periods and was placed parallel to the enemy coast at about 70 miles distance. There were several reasons why the screen may not have been successful, one of which was the difficulty in preventing the bombers from using radio during the course of the assembly.

Among the jammers available to cover the frequency bands of the enemy EW stations, Mandrels and direct-noise amplifiers (Dinas) were the most important. Rugs and Carpets were also considered. Essentially, the problem of jamming the whole EW network involved work on the frequency band from 70 to 220 mc, and the somewhat less important bands from 350 to 380 mc and from 520 to 590 mc. A frequency of about 36 mc was added to this, later in World War II, because there were one or two enemy stations of that frequency on the Dutch coast. The type of station against which jamming was necessary covered the whole range from the old-type Freya with relatively low gain and low power to the big Hoarding and the Jagdschloss. When considerations of beamwidth are taken into account, it is easy to realize how difficult was the problem of screening a formation, especially at short distances from the enemy chain of radar stations. Any solution of this problem involved about seven to ten aircraft spread over a 100-mile front, each aircraft carrying from 10 to 20 jammers and a corresponding number of antennas. These figures are quoted to give an idea of the order of magnitude of the effort involved, and effective screening was not expected after the formation was within 50 miles of the enemy radar stations.

The screen project was revived again in December 1944, partially because of the possibility of serious trouble from the enemy jet aircraft. A thorough study of the problem was made by the Operational Analysis Section, Eighth Air Force, and by ABL-15. At the time, it was expected that the screen would probably not be used unless the fighter threat increased; however, it was considered to be a weapon which should be available for use at any time. The 36th Squadron was fitted with a large number of jamming transmitters. Ten B-24's were each equipped with nine APT-1's and one ARQ-8, with the barrage frequency distributed according to plan to cover both narrow and wide beams over the frequency range of from 80 to 200 mc. These aircraft were to be flown about 80 miles from the Dutch coast, 9 miles apart, at a 15,000-ft altitude. This screen was not used except on an experimental basis.

In connection with the radar screening project, an intercept program was undertaken by the Air Forces to determine, as accurately as possible, what radar stations were being used by the enemy to provide EW. A Ferret aircraft was equipped with APR-4 and S-27 intercept receivers and was flown on a number of missions during the assembly period of the 8th Air Force bombers, and enemy signals and frequencies were then recorded. Since the German EW net continued to spread in frequency and the number of different types of radar equipments which were used for this purpose continually increased, the obtaining of such information was important in order to insure reasonable performance from the screen.

In order to overcome the possibility that the enemy might profit from our own v-h-f communications during assembly periods, a communications screening project was undertaken by the 8th Air Force with laboratory aid. Experiments were run which determined that our own very high frequency could be jammed in such a way as to prevent reception at a long distance by enemy intercept stations on the Dutch coast, while permitting normal traffic between the aircraft and the ground during the rendezvous. Five B-24 aircraft were provided for the purpose and each carried 12 SCR-522 v-h-f communication equipments which were noise-modulated by Gastons (ARA-3's). This v-h-f screen was flown regularly after it was completed.

In October 1944, ABL-15 was requested by the Ninth Air Force to provide improved equipment for their enemy v-h-f listening (Y) stations. Several Fuge 16 receivers with 60-c power supplies for ground operation were provided and installed.

The British were the first to work on the device called Perfectos, which was intended to trigger the German identification friend or foe, permitting the range and direction of German fighter aircraft to be found by Allied fighters. Homing facilities were provided so that an interception could be made. ABL commenced work on this development early in 1945 to modify it for use by the Eighth Air Force, whose requirements differed from those of the RAF in that a considerably increased range was desired, and installations were wanted in American fighters. The Perfectos transmitter was a modified SCR-729, and the power output was increased to 5 kw from the original figure of about 750 w by adding a modified unit from a Navy ASB radar. A new homing antenna system was designed by the antenna group and was found to be very satisfactory. Ranges of 80 to 100 miles were obtained on test flights. The first aircraft to go into operation was a Mosquito, which had been chosen because it was expected that the development could be completed sooner on this aircraft. Unfortunately, it was shot down by friendly fighters over enemy territory on its second mission. A two-seater P-47 was next fitted with a Perfectos equipment. It was flown operationally and was probably responsible for the location and subsequent destruction of two ME-262's. Further operations were unsuccessful as a result of lack of enemy fighter opposition. An installation of Perfectos in a two-seater P-51 was just completed as World War II ended and therefore did not go into operational use.

Another successful development which was completed too late for operational use but which might have had some application in the Pacific war, was the project Curtain. This was a device, installed in a two-seater aircraft, for homing on enemy v-h-f and Benito transmissions. A German Fuge 16ZY homing receiver was used with the normal loop and stub antennas replaced with three vertical quarter-wave Whip antennas which were so located and phased as to give the same pattern as the loop and stub. This arrangement was used in order to obtain maximum sensitivity, which was felt to be an essential. A successful homing range of over 200 miles was obtained with this equipment.

14.7.4 Miscellaneous

In connection with the RCM activities in the ETO, several problems arose which were not directly related to countermeasures against flak or fighters. This section of the report intends to summarize the work done on two of the most important of these miscellaneous problems.

One of the developments related to RCM has

been, in all theaters of war, the work on methods to decrease the vulnerability of the Allied sets to enemy jamming. One typical example is given by the work on the v-h-f transmitter used by all Allied aircraft. Complaints were received at the end of 1942 from several units of the American Air Forces that the SCR-522 transmitter was quite often seriously jammed over enemy territory. An investigation proved that the jamming might have been unintentional in that it was coming from the German Freya radar station operating in the same frequency band. A study of the SCR-522 proved that it was particularly susceptible to this type of interference. It was found possible to improve the situation by a very large factor by making a simple modification to the receiver. This modification involved changing some time constants in the receiver circuit and introducing a limiter to clip off pulses of particularly large amplitude. Eventually all sets used by all the U. S. Air Forces were modified according to the specifications of the American-British Laboratory where the developments were carried out. A similar type of work was done on v-h-f ground and ship-borne stations.

For the purpose of planning RCM operations a theoretical analysis of the parameters involved is seldom sufficient. It is, therefore, extremely useful to test RCM methods and tactics against a captured or simulated enemy equipment so as to determine the best methods of interfering with its operation. Several tests were flown in the ETO against a captured German Small Wurzburg to determine the effectiveness of Chaff and Carpet. It would be beyond the scope of this report to give a detailed analysis of all the tests which took place. It is sufficient to state that tests were made in order to determine the optimum amount of Chaff and the effectiveness of some of the enemy's AJ devices; to determine the effectiveness of special tactics involving the use of Chaff and the effectiveness of Chaff bombs; to determine the optimum spacing between jammers in a barrage for different altitudes and for different formations; and, finally, to determine the extent of protection offered by all these tactics for different altitudes and distances of the formation from the radar set.

Another test which may be singled out for special mention was one in which a special formation was flown by one of the wings of the 8th Air Force. This special formation had the purpose of increasing to the maximum possible amount the concentration of aircraft over the target. The purpose of the test was not only to check the feasibility of such a tactic but also to determine what advantages would accrue to the use of RCM by increasing the number of jammers present, at a definite time, within the beamwidth of the enemy radar scope. All the tests mentioned above were completed with a variable degree of success. The overall result was to supply the RCM planners with the data necessary for their operation. These tests were also particularly useful because they furnished one of the best proofs of the efficiency of RCM and therefore provided a basis for discussing the necessity of the RCM program with operational personnel when no other proof of the usefulness of RCM was forthcoming either from intelligence or from the analysis of battle damage figures.

At the end of the war in Europe a series of tests was conducted in ETO in order to supply information to the RCM operational theaters in the Pacific. The Japanese employed a gun-laying set which was copied from the British GL Mark II. It was, therefore, decided to simulate tactics employed in the Pacific Theaters against one of these original British sets.

With the help of civilian technical advisers and the cooperation of the British units, the Eighth Air Force conducted a long series of tests to determine the effectiveness of Rope and electronic jammers against the set. The data obtained were invaluable in supplying quantitative analyses of the effectiveness of all these sets and were used in the last month of war against Japan in order to help formulate the tactics flown by the 21st Bomber Command against the heavily defended targets of Japan.

The German development of AJ devices was known to have included means for taking advantage of a jammer antenna of the type which was originally used and which produced vertically polarized signals. This development, called Stendal B by the Germans, was intended to permit measurement of range with the Wurz-

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burg antenna cross-polarized with the jammer antenna. Fear of this development caused the circularly polarized AS-69 Fishhook antenna to receive a great deal of consideration and it was deemed very advantageous for use in the Carpet program. In addition, since the field pattern of this antenna was felt to be more suitable than that of the stub antenna used previously, it was felt highly important to use the antenna in the Eighth Air Force Carpet program. Since the fishhook antenna was not available in quantities from the United States in April 1944, it was decided to manufacture it at the Air Corps Base Air Depot. ABL-15 simplified the design of the antenna and a large number were produced in the theater and were later supplemented by production antennas from the United States.

In November 1944, field patterns which were taken of the AS-69 antenna showed an appreciable variation from the ideal pattern over the extended Wurzburg frequency range which was being encountered at that time. Modifications to the antenna were made which permitted its use in the range 450 to 500 mc. A considerable number of modification kits were later made in the theater at the base air depot.

14.7.5 The Effectiveness of the RCM Program

An abstract of the ABL report[806] evaluating the flak countermeasures program of the air forces is included below.

At the end of the war in Europe, ABL, the British branch of the Radio Research Laboratory, participated in an intelligence program whose main objective was to determine the effectiveness of the radar countermeasures program that was carried out by the American heavy bomber forces against the German Flak radar. In connection with this program, information on the German scientific organization, German radar, and Japanese liaison was collected. The sources of information were: interrogations of German officers responsible for Flak defense, interrogations of German Flak radar operators, interrogations of German scientists in charge of work on radar and anti-jamming problems, interrogations of engineers in charge of radar development in industry, inspection of German radar research laboratories and service installations, and examination of numerous German documents.

German Flak Organization. The German Flak defense utilized about 16,000 heavy Flak guns and about 3,000 Flak-control radars, Wurzburgs and Mannheims. The "normal" battery was comprised of four to eight guns, the larger guns (105, 128mm) being used in smaller groups than the 88 mm guns, and a control center. The "gross" battery, a combination of two to six normal batteries, had a correspondingly larger number of guns and, in addition, had at least two complete control installations. A control installation included optical and radar tracking gear and a prediction-computer unit. Radar-range and visual-angle

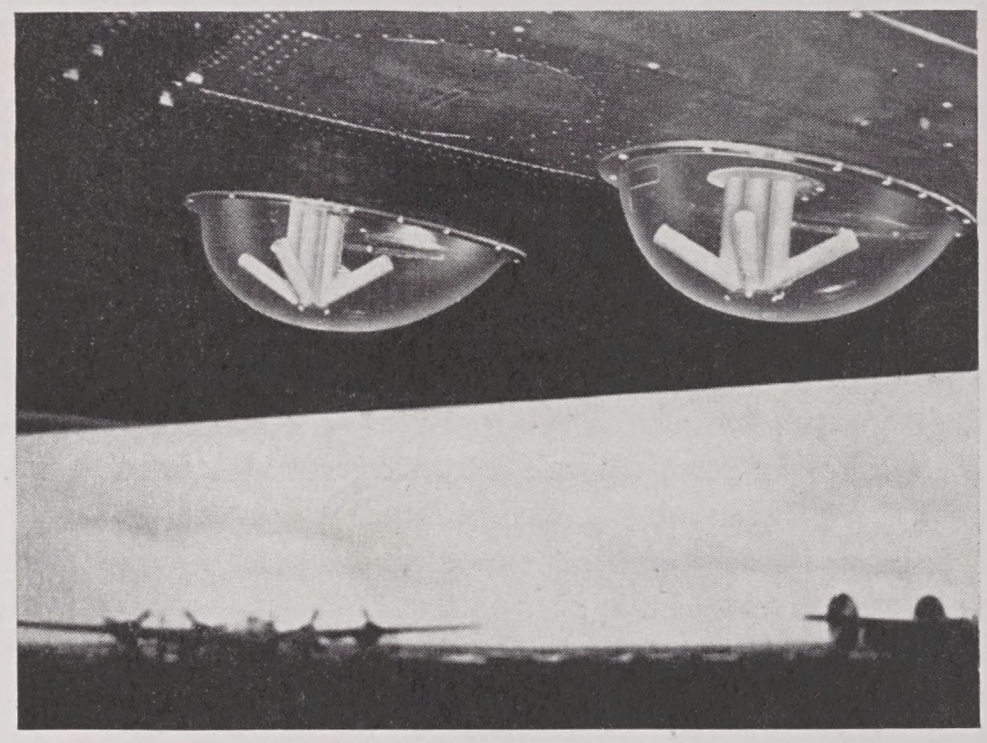


FIGURE 10. Dual installation of fishhook antennas on the belly of a B-24. Such an antenna was intended to deliver circularly polarized jamming energy at relatively low angles to the horizon in the Wurzburg frequency bands.

tracking was used whenever conditions permitted although when the radar was jammed, complete optical tracking was required. This, of course, was impossible under overcast conditions and a makeshift Flak procedure known as "directed barrage" was then employed. At a very limited number of target areas, extensive and accurate equipment was employed for transmitting and converting data for use at remote locations. Generally, the substitute Flak-control procedures were much less effective than full tracking control.

German Scientific Organization and Radar Research. Radar research started in Germany in 1934 and in 1936 contracts were awarded to several manufacturing concerns for the development of operational radars. However, no radar production resulted until 1938. Large scale production of the Wurzburg, which was the standard Flak-control radar throughout the war, started in 1940. All the early radars operated at frequencies below 600 Mc, and no significant work on research in the centimeter band was started until about 1943. Around the end of 1940, the High Command evidently decided that the war would be won in a short time and that existing radars and other scientific equipment would be adequate for a short war. As a result they stopped all

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research which would not produce finished weapons in less than a year and drafted many of the scientists into the Army (some exceptions existed, such as rocket, atomic explosive, and jet aircraft research). This policy was in effect until early in 1943, and as a result research stagnated.

In January 1943, the first Allied cm. radar equipment, the British H2S system, was captured. The High Command was taken entirely by surprise at the appearance of cm. radar equipment and evidently was not aware of the status of Allied radar research. At about the same time they evidently realized the war was going to be a long and hard one and decided that research must be revitalized and reorganized. As a result a Bevollmächtiger (Plenipotentiary) was appointed for each of several branches of science. This man had absolute control of all research work done in his field. Radar and anti-jamming research were under the control of the Bevollmächtiger für Hochfrequenz Forschung (Plenipotentiary for high-frequency research). A committee known as the SKFM (Special Committee for Radar) was also set-up under the Ministry of Armament and War Production which controlled the overall radar and anti-jamming problem, coordinating operational requirements, research, development, and production.

During 1943 most of the efforts of the BHF were expended in expanding research facilities and copying the British H2S, and as a result very few new devices were developed. However, at the beginning of 1944, the first copies of the H2S were completed and work was started on the design of a complete line of 9 cm. radars. About the same time they received another shock with the capture of our H2X, 3 cm. radar equipment. Immediately work was started on investigation of 3 cm. techniques. Later in the year they learned from intelligence sources of Allied work on equipments in the 1.0-1.5 cm. band and again they started new work at wavelengths of 1.5 to 1.0 and this time also at 0.8, 0.7, 0.6, and 0.5 cm. Early in 1945, the first experimental 9 cm. GL, AI, etc., equipments were completed, but the war was over before any appreciable number were placed in service.

In general, the German radar program may be described as a frenzied attempt to catch up with the Allies. However, they never succeeded in producing any significant number of operational equipments, and hence, in spite of the tremendous effort expended, the program was a failure. In general, the state of technical radar development at the end of the war was similar to that existing in Allied laboratories in about 1942.

Radar Countermeasures War. H2X and RCM were partners in the blind bombing attacks on Germany. RCM's job was to "blind" the German Flak radars and hence keep the Flak losses down to a value which made blind bombing practical. Both were introduced in the bombing war against Germany at approximately the same time and were used together throughout the war. RCM also was used during visual missions to deny the Germans the accurate range information obtainable from their unjammed radars and force them to use optical tracking alone. The following paragraphs present a brief résumé of the RCM war.

The Germans first considered the use of Window, Chaff (dipole confusion reflectors), as a means of jamming radars in 1940, but immediately decided they would stand to lose a lot more than they would gain if the Allies used it against them. As a result they used "Ostrich" tactics and kept it under cover hoping the Allies would not think of it. In 1942, they conducted a few tests on Window and evidently confirmed their suspicions as they kept the matter more secret than ever. They made no plans for the development of anti-jamming devices against Window for their radar, and as a result were caught entirely by surprise and unprepared when the British first used it against them on July 25, 1943. The Window completely jammed their radars at first and caused a tremendous amount of excitement in military circles. As a result the development of anti-Window devices was given the highest priority, and a very large number of scientists were put to work on the problem.

The RCM war developed into a battle of attack and counter-attack, this battle being opened with the attack represented by the first British use of Window. Successive "offensives" in the case of the U.S.A.A.F. were introduced with the first use of Carpet, October 1943; and the first use of combined Carpet and Window, December 1943. A gradual build-up of the Window program through the Summer of 1944 led up to the last all-out RCM offensive—the full scale application of Carpet and Window from Fall 1944, to the end of the war.

German counter-offensives were, in general, efforts to patch up their Flak control radars to enable operation through our jamming. As the battle developed, there were sufficient changes in the jamming due to the introduction of new jamming and due to the general increase in jamming intensity to render the Germans' anti-jamming efforts virtually ineffective. The Germans themselves felt they were always one step behind and never succeeded in catching up with U.S.A.A.F. jamming. After the start of the full countermeasures program in Fall 1944, the German radars were almost useless.

A tremendous amount of scientific effort was expended in trying to overcome the effects of Allied jamming, but it was practically all in vain. From the Fall of 1943 on, an average of 50 per cent of the technical personnel engaged in high-frequency research worked on the anti-jamming program. In the late Summer of 1944, this figure probably approached 90 per cent. In all about 5,000 technically trained persons were engaged in high-frequency research, and therefore an average of about 2,500 were working on anti-jamming devices. Almost the entire remainder were engaged in cm. radar research.

From German reports, the combined use of Carpet and Window jamming was by far the most effective as usually some anti-jamming device would help somewhat against either when used alone.

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RCM Effectiveness. An average of a number of German estimates on the overall reduction in the effectiveness of radar controlled Flak from September 1944 on, reveals that the use of RCM by the American heavy bomber forces reduced the overall effectiveness to about one-quarter of the value obtained in the absence of jamming. In the case of the U.S. 8th Air Force, about 40 per cent of the strategic missions flown in this period were under 8/10ths or heavier cloud cover, which means that the reduction of radar Flak effectiveness was, in the overall program, of major importance in saving bombers and crews. Before September 1944, jamming was having an important effect on German Flak, but it has not been possible to obtain estimates as to the extent of the effect in this earlier period. It can be concluded with certainty that RCM had a marked success in protecting heavy bombers on daylight raids, particularly on those runs under blind conditions.

14.8 UNITED STATES AID TO THE RCM PROGRAM OF THE RAF

14.8.1 Work of the First United States Technical Group

Late in 1942, a number of engineers from the Radio Research Laboratory and the Radiation Laboratory were sent to England, to assist the British with their RCM program and to provide liaison between the British and the American Laboratories. The first of the group arrived in England in November 1942 and were assigned to Telecommunications Research Establishment [TRE], RAF; to Admiralty Signal Establishment [ASE], Royal Navy; and to Air Defense Research and Development Establishment [ADRDE], Army. These men immediately commenced work on projects in the British laboratories very much on the same basis as the regular research staff members of these institutions. The more important projects on which this group worked and the operational use to which the equipment was put are briefly summarized below.

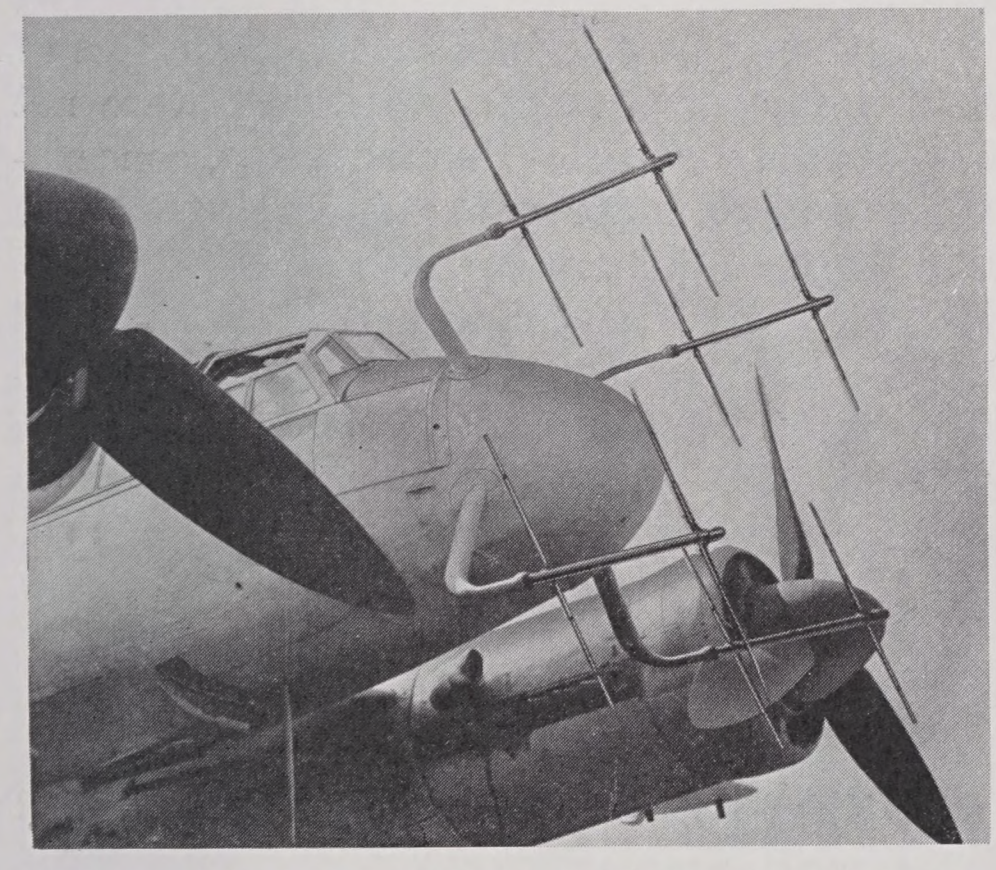


FIGURE 11. German night fighter aircraft with antenna array for one of the later models of Lichtenstein, AI type radar.

BOOZER

Boozer was a code name applied to a simple warning receiver operating in the German AI, GL, and GCI bands in the vicinity of 500 mc. The receiver was intended to provide the British night bombers with a warning of the presence of enemy radar by means of simple indicator lights, thus permitting evasive action to be taken at the correct moment. The British Boozer was widely used during the great night bombing offensive in 1943, although its usefulness was difficult to assess.

BAGFUL

This receiver was designed to search for and automatically record radar signals. The first operational use of Bagful was by the 8th Air Force, and this receiver played an important part in the initial American investigation of German radar.

AIR CIGAR

One of the most important of the British RCM operations was that known as Air Cigar. In this operation, jammers were carried in several of the night bombers to disrupt the v-h-f communications used by the enemy in his night fighter GCI system. A receiver which provided means for rapidly setting the jammers on the enemy's frequency was developed. This receiver provided a panoramic presentation of the enemy communication band and by means of a marker pip permitted the operator to set his jamming transmitter exactly on the enemy channel. The Air Cigar operation was used extensively, beginning in the fall of 1943, and was generally conceded to be extremely successful.

CARPET II

This was a jamming transmitter designed for the purpose of automatically searching for and locking on enemy radar frequencies. A discriminator circuit developed in conjunction with this apparatus which permitted the transmitter to be set precisely to the center of both weak and strong signals was subsequently used in other applications, including Bagful. Carpet II was produced and used on a large scale on small landing craft in the invasion and later was also employed in the British night bombers to supplement Window.

Although the direct participation of this initial technical group in the RCM program of the RAF was discontinued when the American-British Laboratory was set up in the ETO, an exchange of RCM technical assistance and equipment between the Americans and the British continued throughout the rest of World War II.

14.8.2 Big Ben

The German V-2 rocket was given the code name Big Ben. The defense of Britain against Big Ben was primarily a British problem and was the responsibility of the RAF. However, American equipment and technical aid also played a part in the program. In the initial phase of the Big Ben scare, very little was known about the weapon. It was felt to be a potential threat of great importance against Britain, and for that reason very high priority was placed on any measures designed to operate against it. Initially, then, so little was known about the problem that any and all measures which appeared to have chance of success were taken with the utmost possible speed.

A series of listening stations along the east coast of Britain were alerted and put on constant guard against Big Ben control signals. The British 192nd Squadron conducted regular flights in an attempt to correlate sightings of the rocket with actual signals heard. Equipment recovered from rockets which landed in Britain was examined with extreme care. From these analyses, some successful reconstructions of the equipment functions were made.

A number of h-f transmitters varying in power output from 10 to 50 kw were modified to operate on the suspected Big Ben control signal frequencies and were set up along the probable line of flight of the rocket, assuming that London was the main target. The 50-kw Elephant Cigar, which was an American transmitter, was modified so that it would cover the probable Big Ben frequencies and also so that it could be tuned quickly as a spot jammer. Several 50-kw transmitters were obtained from America, and a number of American 15-kw equipments, which were originally designed to jam the German v-h-f band, were delivered and modified for possible Big Ben jamming.

The initial phase of the Big Ben problem involved doing the best possible job in searching for the radio signals which presumably were used by the enemy for a number of purposes connected with the precise control of the rocket. This search job proved to be an exceedingly difficult problem because of the very short duration of the transmissions and because of the fact that, at least in the early phases of the work, the search had to be done from aircraft because of the improbability of receiving any signals in England on the ground. Most of the attempts to intercept the signals were not successful and actually the knowledge concerning the control signals was obtained from the analysis of equipment which had crashed.

Fortunately, the advance of the ground armies eventually greatly reduced the importance of the Big Ben threat, and, as this occurred, the priority on countermeasures dropped accordingly.

14.8.3 Tuba

The Tuba project is an example of an operational need stimulating the development of a completely new technique which progressed to operational use. For this reason, despite the fact that the operational importance of the device was much lower than generally expected, it is worth while to outline briefly the history of this program.

By the summer and the fall of 1942, the Germans were using their Lichtenstein AI

radar on their night fighters over Germany and German-occupied territory with sufficient effectiveness to be an important factor in the losses sustained by the RAF Bomber Command. The low power of the enemy AI and the relatively poor antenna system, plus the fact that the receiver was of superregenerative type, made the use of electronic jamming appear attractive. Jamming of the enemy AI could be carried on from ground bases with powerful jammers, by jammers carried in all of the bombers, or by use of medium-power jammers in especially equipped airplanes flown for that purpose along the bomber trail. The second alternative did not appear attractive because of the danger that the enemy could home on the jammer carried by the bomber. The other two alternatives were both considered and employed.

The first example of jamming the enemy AI from the ground took place during the middle of 1942, when the RAF set up a series of jammers with power of the order of 50 to 100 w and with a rotatable high-gain directional antenna. These jammers were monitored from the ground by listening to the enemy signals and by tuning the jammers on the frequency which appeared active.

This system had several shortcomings, and therefore the idea was suggested that a powerful ground-based jammer could be built to cover the whole band of the enemy AI radar set. It was also required that the jamming power be sufficient to jam enemy sets within a wide angle from the ground base. It was easy to see that powers of the order of magnitude of 15 to 50 kw were required for the job. Such a power, at frequencies of the order of magnitude of 500 mc, had never been obtained before. Actually, even powers of the order of 1 kw were far from practical realization. It so happened, however, that the NDRC had been sponsoring the development[e] of a special tetrode oscillator.[f] This tube seemed capable of giving the power required and the needs expressed by the British Bomber Command were strong enough to make the whole program worth while.

The development of a transmitter using this tube was done at the Harvard Radio Research Laboratory. The jammer was to deliver about 50 kw and two transmitters were required with a total bandwidth of about 10 mc each, so that two units could cover the whole enemy 20-mc band. Together with the AI jamming, a high-power communication jammer was also designed to interfere with the enemy ground-to-air and air-to-ground communications. It was found very difficult to obtain a wide-band modulation of the Sloan tube, but powers of the order of magnitude required could be achieved with a continuously pumped tube. The first unit had two 25-kw transmitters and was mounted in six trucks. The British were supposed to take care of the construction of the antenna, but for several reasons no antenna was available when, in February 1944, the first complete unit was shipped from Boston to England. The equipment was made operational 3 or 4 weeks after its arrival in Great Britain and, since the antenna problem had not been solved, it was necessary to improvise a horn made of chicken wire. By mid-July 1944, operational use of the equipment had begun. Crews were trained and the American civilian technical crew returned to the United States.

In the late summer of 1943, it had become apparent that an obvious German reaction to the use of any AI jammer would be to shift the frequencies either up or down. For this reason, new tubes were designed to cover frequencies from 345 to 375 mc and from 470 to 540 mc. A new Model IV was subsequently built tunable on the whole range of 350 to 600 mc. This new tube was also easier to modulate. With the new tubes available, one of the two new units which were being prepared for the British had to be equipped with the broad-band tube. Work on making the second and third units operational began in July 1944. By January 1945, the two new units were completed and three units were available in England.

During the summer of 1944, the first Tuba equipment was used operationally on a more or less regular schedule operating several hours a day and several times a week in coordination

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[e] By Dr. David Sloan, then of the Westinghouse Research Laboratory.

[f] Originated by Dr. Sloan and Dr. L. C. Marshall at the University of California.

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with bomber command operation. Operational use was stopped in October 1944, because the enemy had ceased any extensive use of the 500-mc AI in favor of a set operating at a much lower frequency. It must be noted, however, that the operation of the equipment was satisfactory in all respects and this is significant if one considers that never before had power of the order of magnitude of 15 or 20 kw been available in the 500-mc band.

As noted before, the operation of the first Tuba unit was interrupted in October 1944, long before the second and third units arrived in England. Neither of these two units was, therefore, used, but plans had been made for moving one of them to the European continent when World War II ended.

It is difficult to evaluate the effectiveness of the Tuba project. The Tuba became operational just at the time when the Germans were changing from the Lichtenstein to the much superior SN-2, which operated at 90 mc, out of the frequency range of Tuba. However, tests carried on in this country did show that a Tuba transmitter (Figure 12) should have been effective in jamming AI sets operating within 1 or 2 mc of its carrier at distances of 200 miles or less from the jammer.

14.9 NAVAL RCM

14.9.1 Use of RCM in Early Naval Operations

The use of RCM by the U. S. Navy was extensive and had the following purposes. First of all, it involved countermeasures against guided missiles launched by enemy aircraft in attacking Allied shipping. Second, it involved the use of countermeasures and radar deception both for the purpose of diversion and for protection against detection and radar fire control by the enemy. Deception was used to simulate landings behind the enemy lines in support of a ground attack, in order to capture isolated islands by giving the enemy the impression that a large force was concentrated in the surround-

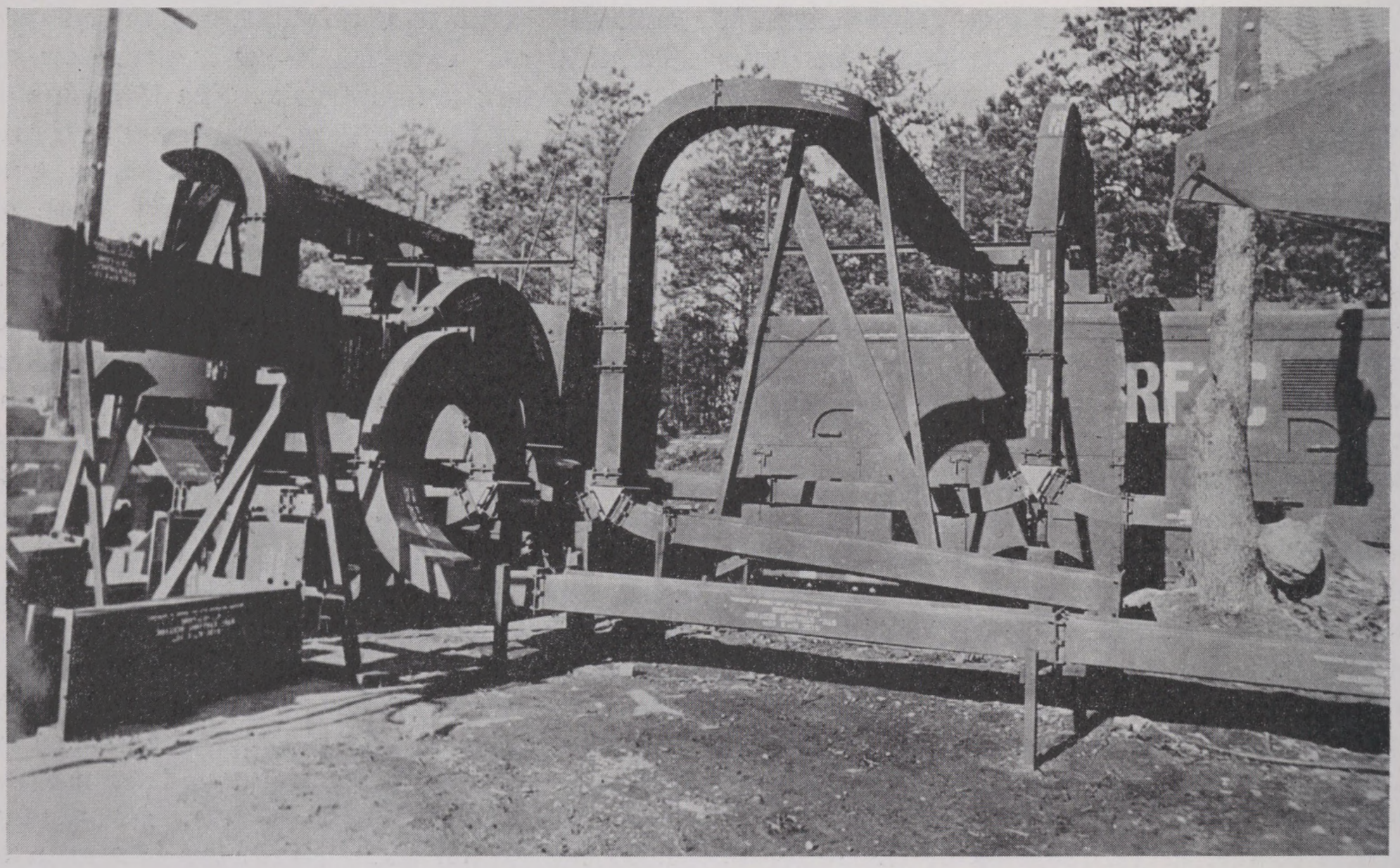


FIGURE 12. The wave-guide "switch yard" of the high-power, ground-based jamming transmitter, Tuba.

ing waters, and was finally employed as an important part of the overall plan in the invasions of Normandy and southern France.

Guided Missiles

In 1941, British Intelligence gave the first news of the development of guided missiles by the Germans. The first experimental models developed by the enemy were found to be successful about the middle or end of 1942. The first example of successful attack by the glide bombs Hs-293 was when corvettes in the Bay of Biscay were attacked in 1943 while on an antisubmarine patrol. One of these corvettes was sunk and another was damaged. In October 1943, two special destroyer escorts were equipped by the U. S. Navy, on a very high priority, with search and jamming equipment in the band in which the enemy was expected to be operating. These destroyer escorts were sent to the MTO; they were attacked in November off the Algerian coast. Intercept signals were correlated with the attack, and information was obtained on the frequency and the type of modulation employed. More equipment was developed and built, and more ships were equipped with it. In the winter of 1943-1944, the number of RCM sets employed increased, so that in February 1944 all the convoys from Oran to Bizerte had at least two ships equipped with guided missile jammers to accompany them. After that, no ship in any protected convoy was hit by glide bombs. A little earlier, in January 1944, when the invasion at Anzio took place, the two original jammer ships were present. The enemy made 75 separate attacks against the Allied shipping concentrated near the beachhead; about 125 control signals were jammed in a 2-month period. Five ships were hit, but two of these were not in the immediate area of the destroyer escorts.

The number of ships equipped with jammers during the year 1944 increased continuously. Frequent reports were obtained of guided missile signals successfully jammed. Altogether, the percentage of hits dropped to the level of ordinary high-level bombing. During the invasion of Normandy and southern France, several glide bomb attacks were reported, most of which missed. Several examples were reported of glide bombs, headed directly for ships, which broke off under jamming and crashed into the sea.

Intelligence reports received after V-E Day contained claims by the Germans that Allied jamming had not been the major cause for the disappearance of the enemy's guided missile attacks. They claimed that the real reasons were (1) that Allied air superiority prevented the parent aircraft from flying close enough to the targets and (2) that lucky hits by one of the attacking strategic air forces had destroyed all the aircraft equipped with the necessary installations and these were found very difficult to substitute. It is well known that the strategic situation of the enemy air arm deteriorated continuously during the year 1944, and it is clear that all of the above factors combined to make the danger of guided missiles less serious than it originally appeared. One result traceable to the use of countermeasures was that enemy scientists responsible for the development work became prejudiced against any type of radio control which was not very carefully protected against Allied jamming. The enemy development of new weapons was thereby slowed down considerably and the equipment designed became very complicated and difficult to build. By the end of World War II, no newly developed guided missile had seen operational use against Allied ships.

Deception

As mentioned before, several operations were carried on in which RCM deception played an important part. A special Navy force was equipped with RCM sets and deception devices consisting of barrage balloons, corner reflectors, and so on. This force is credited with capturing islands off the coast of Italy. A few boats, carrying countermeasures sets (intentionally made not completely effective) and deception devices of all descriptions, were able to simulate the existence of a force comprising battleships and other large vessels. As they approached the islands, surrender was requested from the enemy and was obtained solely on the basis of a bluff supported by the indications appearing on the enemy's radar scope. This tactic, originally used for the cap-

ture of islands off the coast of Naples, was repeated to simulate the approach of a landing force at a point north of the real beachhead at Salerno. This particular deception is credited with delaying by several days the operational employment of one of the enemy's crack divisions against our invading forces. The same small force was also employed in the first part of 1944 to simulate another landing north of the Anzio beachhead; the purpose of this tactic was to help the ground forces attacking from the south in joining the forces which had remained on the Anzio beachhead for several months.

A substantial RCM effort was also carried on to protect the main invading force at Salerno. Here the purpose was to use countermeasures to hide the exact spot of landing during the night before D-Day, though it could not hide the fact that an operation was impending. A large number of Rug transmitters were sent from the United States by very high priority. These sets arrived in Africa 5 days before the operation and were installed to protect seven convoys by jamming the enemy coastwatcher frequency band. One evidence of their effectiveness was that several batteries of German 88's near Salerno were firing very wildly, and, in fact, shells were fired over the convoys and landed on the opposite shore where there were some German troops.

When the island of Elba was invaded, a strong diversionary effort was carried on along the northern shore in support of the amphibious force which attacked from the south. PT boats carrying balloons, corner reflectors, and RCM jammers approached the northern shore under cover of a dense smoke screen. Sonic devices with very powerful loudspeakers simulated the noise of landing boats approaching the beach and of tanks coming out of them. Rocket fire was directed against the shore positions and dummies were dropped on the surf to simulate the landing of infantry.

14.9.2 RCM in the Invasion of Normandy

The naval RCM plan of the operation Neptune, as the invasion of Normandy was called, was the result of a great deal of study by the British and American operational groups and technical personnel.

The enemy coastline, particularly in Normandy, was very well protected by a number of radar chains which were designed to supply EW facilities and GL information to coastal batteries. In addition, enemy ASV was also dangerous to the success of the operation. Therefore, the use of RCM against the enemy coastal and airborne radar was a potentially important part of the naval invasion program.

The operational program from the naval RCM standpoint could be broken down into two parts: first, RCM could be applied in such a way as to deny the enemy information concerning the time and location of the attack and, in addition, feint attacks could be made feasible by proper application of countermeasures; second, as soon as the ships were within range of the shore batteries, enemy fire-control radar, which was a potentially serious threat, could be neutralized by RCM.

Prior to the invasion of Normandy, all the known radar stations along the enemy coast were subjected to direct attack by strafing and rocket fire. This was done over an area sufficiently large to divert suspicion from the chosen landing beaches.

The locations of the enemy radar stations were obtained by several methods, such as intelligence, photo-reconnaissance, and the taking of DF fixes. British listening stations supplied a great part of the information, and the British set up, at appropriate points along the coast of England, special DF-ing equipment known as Ping Pong, which was capable of obtaining very accurate fixes on enemy radar signals. In addition, the British attempted to obtain more information concerning the German naval RCM by sending small boats equipped with search gear in toward the enemy coast within range of enemy radar.

The main attack force was made up of both British and American vessels, and these forces went in to separate landing areas. The jammers were not turned on until shortly before the ships came within range of enemy radar. Jammers were carried in the attack forces, in landing craft, as well as in a number of battle-

ships, cruisers, destroyers, headquarter ships, and troop transports. In addition to the main attack, feints were made to the north and to the south. RCM equipment played a large part in these diversionary attacks, which were carried through by small harbor defense motor launches, and was effective in creating the impression that large forces were approaching the coast. In addition to these diversions, Window-dropping aircraft were used in support of the airborne landings. Such aircraft, by laying Window trails, attempted to confuse the enemy as to the location and direction of the airborne attacks.

Protection of the attacking force from enemy coastal guns was a difficult problem, although it was simplified considerably by the direct attacks which had been made on the radar stations. The magnitude of the RCM effort was largely determined by the availability of the jamming equipment. The power required to self-screen a big surface vessel rapidly becomes very large as the ship approaches the radar station, and it was impossible, therefore, to give complete protection to all ships in the attacking force. Low-power Carpet II jammers with an output of ½ w, adjusted to cover the Seetakt and Wurzburg bands, with a few Mandrel, Carpet I, and Rug jammers, were placed in the landing craft partly for self-protection and partly in the hope that when they were close to the beach some screening of the transport area would result from jamming through the side lobes of the enemy radar. The Mandrels were set to known frequencies of the enemy stations, these frequencies having been carefully measured prior to the operation. Likewise, Rug and Carpet I jammers were used to provide a barrage across the most probable enemy frequencies. Pimpernels (used only on British ships) and Carpet II's were adjusted to search the bands from 530 to 590 mc, 460 to 508 mc, and 330 to 400 mc, each set covering a selected 40 mc, of these ranges.

In the Neptune operation, it was necessary for both the United States and British Navies to rely for the most part on RCM equipment which was originally designed for aircraft installation. In the U. S. ships, only 12 out of the 88 radar jamming equipments which were installed were designed for shipboard use. These 12 equipments were the relatively high-power Broadloom (CXFR) and TDY jammers, which were used on three battleships, two cruisers, two destroyers, a headquarters ship, and several troop transports. The complete schedule of fittings in American ships is shown in Table 4.

TABLE 4. Schedule of fittings in American ships.

Transmitter Installations Set	LCTA	LCTA-5	LCGL	Total
British Carpet II (h-f)	16	..	7	23
British Carpet II (l-f)	16	..	3	19
American Mandrel	4	1	4	9
British Mandrel	..	1	..	1
Carpet I	..	..	10	10
Rug	..	4	10	14
				76

Monitoring Installations	Frequency range covered
USS *Ancon*	
1 S-27 with RBW pan adapter	28-143 mc
1 APR-1 with TN-2 and RDK pan adapter	80-300 mc
2 APR-1 with TN-3 and RDK pan adapter	300-1,000 mc
2 RDL (Blinker)	250-450 mc; 450-650 mc
1 APR-5	1,000-3,000 mc
2 Oscilloscopes (for pulse analysis)	
2 Beat-frequency oscillators (for pulse analysis)	
USS *Tuscaloosa*	
Same as above with the addition of the following:	
1 APR-6	3,000-6,000 mc

As previously mentioned, diversionary attacks were made with harbor defense motor launches. The attacks were not expected to be completely effective but were intended to add confusion. In order that the size of these diversions should be made to appear as great as possible, the boats taking part towed balloons with corner reflectors, and aircraft dropping Window flew overhead in a zigzag course slowly progressing towards the coast to give the appearance of a large invasion front slowly moving in. The jammers in these boats were so arranged that the probability of the enemy being able to look through the jamming screen was fairly great, although it was hoped that sufficient jamming would be present to add greatly to the confusion.

These diversionary attacks were operated by the British and were thought to be a very real factor in adding to the general confusion that characterized the enemy's planning at the time

of the attack. Since enemy aircraft carrying ASV radar were a potential threat to the security of the diversions, the diversionary boats carried Moonshine equipment with a special operator so that enemy aircraft using radar would also see apparently large forces. During the operation several signals were heard by these Moonshine operators and apparently were coped with successfully.

Since the equipment used in the RCM installations was in most cases not designed for shipboard use and since there had been little previous experience in the use of RCM on a large scale during an invasion, a great many new installation and equipment problems arose during the preparations for the Neptune operation. During several months preceding the operation, ABL-15 devoted a major part of its efforts to this work and was able to solve most of the problems that arose.

In February 1944, work was commenced on the testing of most of the RCM equipments which were involved in the invasion. This testing was done under simulated operational conditions at the Admiralty Signals Establishment Extension at Tantallon, Scotland, with American technical personnel participating. Since a large amount of American RCM equipment was used in the invasion, the British were eager to obtain assistance from men who were experienced with such equipment. Data were obtained at Tantallon on the jamming ranges of various equipments under different typical conditions, and problems of serviceability and installation were studied. Equipments which were tested at Tantallon included Peter, Pimpernel, Carpet I (APT-2), and Carpet III (APQ-9), Mandrel (APT-3), Dina (APT-1), Rug (APQ-2), Broadloom (CXFR), British Mandrel, and British Carpet II.

Tests were conducted of Peter equipment installed in a harbor defense monitor launch of the Royal Navy. The equipment was intended to function only as a signal-intensifying device in order to increase the apparent size, as seen by the enemy radar, of the ship carrying the equipment. It was hoped that the equipment could be used in a diversionary attack with small boats, which, by means of Peter, would appear to be cruisers. Tests of this equipment operating with a bandwidth of 20 mc and a gain of about 300 mc were fairly satisfactory, although the Royal Navy decided not to use Peter and the project was discontinued. In place of the proposed Peter operation, the diversions used balloons with corner reflectors and Window-dropping aircraft. The use of these methods minimized the importance of frequency spread of enemy stations.

Three German radar sets (a small Wurzburg, Seetakt, and Freya) were available for testing at Tantallon, and with the aid of these it was possible to determine the jamming effectiveness of our equipments when carried on mine sweepers and destroyers. Equipment installation problems were studied at Tantallon to determine whether, for example, British Carpet II, which was an automatic searching jammer, could be used on the same ship with American Mandrel or Carpet I. The results of these studies were too lengthy to give here, but from this experience it was possible later on to make suitable frequency allocations and to choose equipment locations on the actual ships which were to be involved in the invasion.

One of the problems which was encountered at Tantallon in the actual ship installations is worthy of mention. The problem of fitting RCM equipment aboard ship is complicated by the likelihood that it will produce interference to other radar or radio equipment aboard the same or near-by facilities. Rather severe interference was produced by the CXFR-TDY equipments, and interference somewhat less serious was also produced by the AN/APT-3, APT-2, and APQ-2. In the case of the CXFR-TDY the interference came from several different sources such as radiation from power leads carrying interference signals up to 15 mc and direct radiation from the antenna of interference in the region of 30 to 150 mc as well as in the vicinity of the output carrier. The first two types of interference were eliminated by suitable modifications to the equipment, but there was little that could be done about the interference in the bands adjacent to the operating frequency, since it was found that the output spectrum of the transmitter was such that the energy was spread over a very wide band.

SECRET

The U. S. Navy fitted two ships with complete monitoring facilities for continually checking the radar spectrum from 30 to 6,000 mc for new enemy frequencies while the invasion progressed. Since a large percentage of the equipments were designed for airborne operation, makeshift arrangements in fitting the equipments were necessary in many cases.

A very essential part of the technical program was the training of the personnel to operate properly the jamming and monitoring equipments. ABL-15 aided in the training of a large number of Navy officers and technicians. In the case of the jamming transmitters, the training was mainly on the CXFR-TDY equipments where operators were required to monitor the enemy signals and manually tune the equipment to the enemy's frequencies.

Although particular emphasis has been given in this report to the U. S. Navy RCM program in the Normandy invasion, actually British ships carried more RCM equipment and even more American RCM equipment than was carried by the U. S. vessels.

American technical personnel also aided with the installation of RCM equipment in British ships. At a conference held in England, about the first of May 1944, it was decided that ABL-15 because of its commitment to the United States Navy, could not supply sufficient personnel to the Royal Navy. As a result an urgent cable was sent from General Eisenhower to General Marshall asking that sixteen civilian technicians be sent to aid the British. Six days later, nine men from the Radio Research Laboratory and two from the Columbia Broadcasting System arrived in London. Shortly thereafter five additional men arrived from the Radio Research Laboratory. These men together with personnel from the Admiralty Signal Establishment went to work on the ship fitting program. Two hundred and seventy-four RCM equipments were installed in British ships, distributed as follows:[831]

113 Carpet I	17 Pimpernels
1 Carpet III	11 CXFR
24 Rugs	11 Blinkers
27 Mandrels	

It is very difficult to assess the result of countermeasures during the invasion of Normandy. Although the attacks on radar stations, made by the air forces prior to the invasion, were undoubtedly very successful, it is known that in a few instances stations were able to continue operating. The evidence appears to be fairly good that in some cases jamming caused erratic shooting by the enemy coastal batteries. Enemy air opposition was practically absent, particularly during the daytime, and, although there are a few instances of the possible use, by the Germans, of radio-controlled missiles, there were no successful attacks, for which the jamming may have been at least partly responsible.

14.9.3 RCM in the Invasion of Southern France

The role of RCM during the invasion of southern France was very similar to the one played during the invasion of Normandy and other amphibious operations of the same type. In order to achieve at least tactical surprise during the landing operations, RCM can be used to very good advantage for the double purpose of shielding the main attacking force and of misleading the enemy to believe that the attack is coming from a direction other than the real one. In order to achieve the second purpose, diversionary forces are usually employed. During the invasion of southern France, there were three main attacking forces, two diversionary forces, and one so-called support force. As is well known, the three main attacking forces landed on the French coastline east of Toulon. The two diversionary forces attempted diversions, one east and one west of the main attack. The right-flank diversion approached the region of Monaco prior to H-hour and attempted with corner reflectors, balloons, and jamming to create an illusion of a force approaching in that sector. The amount of RCM equipment allocated to this force was extremely small and it was fully expected that this force would be recognized as a diversion by the time it got within 20 miles or so of the coast. After this, the eastern force was to turn westward and eventually rendezvous with the western diversionary force near the main beachhead at about H-plus-2. The left-flank diversion, which operated in the Toulon area, included one destroyer and a number of motor launches and torpedo boats. Balloons, corner reflectors, British Moonshine equipment, a slowly progressing

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trail of Window laid by Air Forces planes, and radar jamming were employed in these diversions. The RCM transmitters were monitored with APR-1 and used as spot jammers. On the night of D-minus-1, the western force was to follow a rather complicated course, eventually coming very close to shore just prior to H-hour, turning away again, then going eastward, and finally meeting the eastern force. It was intended that this force put on a really good spoof, and it was provided with more RCM gear than any other force except the main attacking one. The left-flank diversion operated on the night of D-minus-1 as planned. On D-night, however, bad weather prevented a repeat performance which was planned.

The support force or Sitka force invaded the Island of Hyères several hours prior to H-hour and captured the island. During the actual landing, five guided missiles were reported, one of which sank an LST. It is believed that the other four were definitely jammed and they did not hit any vessels.

Direct action against enemy coastal radar was planned for the invasion of southern France just as it had been planned and used in the invasion of Normandy. Bombs, rockets, and gunfire were used against radar stations but the action was started too late to get substantially good results.

To the jamming carried on by the ship-borne RCM sets, must be added that which was provided by 10 Wellington aircraft of the British night-bombing group, each fitted with 5 Mandrel installations, or a total of 50 jamming sets, which covered the coastline on either side of the beach area. Beaver III from Corsica sealed in the jamming gaps left in the beach area with the use of ground-based jammers consisting of Dina-amplifier combinations. The listening watch carried on during the day of the invasion noted that the coast-watcher stations which were not jammed by either the Wellington aircraft or the ground-based sets were not effectively utilized by the enemy; five out of six went off the air.

It must be added that, in the region where the diversionary forces were supposed to simulate a landing, the enemy was allowed to operate at least during short intervals in order to make it possible for him to "see" the diversionary force.

The RCM plan for the invasion was prepared by the RCM board, which had representatives of MAAF, AFHQ, the U. S. and the Royal Navies, and other interested agencies. The number of RCM installations planned by the U. S. Navy for this operation was about twice the number of installations planned for the United States' part of the invasion of Normandy. There were approximately 200 RCM installations either of the barrage or the manually tuned type. The larger proportion of the sets had to be preset on specified frequencies before the operation. This created a very serious problem for the persons charged with the problem of



FIGURE 13. Members of the First Signal Service Platoon (Special) installing a modified AN/APA-24 direction-finding antenna in the mountains of Corsica for Beaver III mission.

SECRET

installation and operation of the set. On July 25, 1944, which was about 18 days before the invasion, no RCM installation had been completed in any U. S. ship, with the result that the majority of the work was compressed into a few days.

Information and intelligence of the enemy stations were supplied by the coordinated analysis of the previous work of the Ferrets and of the British and American ground listening stations. The work of analysis and specifications had been carried on by an appropriate office of the headquarters of MAAF.

The installation of RCM equipment in all U. S. ships was a race against time. Despite the fact that the RCM plan was a satisfactory one, the actual implementation suffered greatly because of the hurry. In the end, 95 per cent of the RCM installations originally planned were actually completed and set on frequency in some manner according to the predetermined plan.

The total number of RCM transmitters installed and set to frequency was about 260, of which about 80 were installed and operated on British ships and 180 on American vessels. Out of this total of 260, approximately 55 transmitters were manually tuned by operators with APR-1 receivers. The number of transmitters in the three main forces was about 210; the balance, or roughly 15 per cent, was in the support forces and in the two diversions.

In the main forces, equipment was installed on the following classes of U. S. and British ships: 4 battleships, 2 transports, 12 cruisers, 15 destroyers, 24 mine sweepers, 57 auxiliary mine sweepers, 2 mine sweep tenders, and 5 landing craft. In the two diversions, RCM equipment was installed on 1 destroyer, 2 British gunboats, 4 torpedo boats, and 4 sea-rescue launches. Air attacks against radar locations began on D-minus-5, but were hampered by bad weather and most of them were made from D-minus-2 to D-Day. According to some information available, after these attacks there was still an appreciable number of coastal radars in operation on D-Day, as indicated by monitoring stations. Several sites visited by intelligence personnel on D-plus-6-day did not show any sign of damage despite the fact that they had been allegedly attacked and rendered unoperational before D-Day. Despite the fact that the number of sorties flown against radar stations was about 500 (as compared to about 1,400 for Neptune in Normandy), complete elimination of enemy radar by direct air attack was not achieved. This confirms the difficulty and uncertainty involved in this type of operation.

14.10 RCM IN THE GROUND FORCES

For reasons already mentioned, radar countermeasures were not used to a great extent by the ground forces in World War II; a few noteworthy developments took place, however. In order to be prepared for work against possible enemy ground-based jammers, the U. S. Army Signal Corps equipped a number of vans with antennas and receivers capable of intercepting signals in the frequency band 100 to 1,000 mc and of determining the direction of the incoming signal by means of DF-ing antennas. Microwave receivers were also available despite the fact that no enemy efforts in that frequency band occurred during the war. (The possibility of eliminating undesired interference or jamming by means of loop antennas was also considered and typical antennas were built out of material available in the field.)

At the request of the United States Twelfth Army Group, the ABL undertook the development of a device for simplifying radio spoofing operations. The device was patterned after a British development and was intended to simulate (with one or more transmitters) the operation of a normal Army communication set. The equipment was developed but not used operationally because World War II ended. It may be worth mentioning, however, that in this equipment (known by the code name of Elmer) the desired sequence of messages, consisting of normal traffic and replies from an Army net, was recorded on a magnetic wire tape. Since in a normal situation the various transmitters on a net would have somewhat different characteristics, means were provided either to control several actual transmitters or to simulate several equipments by small shifts in frequencies and any desired shift in power output. At

the end of a transmission, a controlled signal on the record automatically selected the proper station to reply.

Other work involving RCM weapons, but with a completely different purpose, was the use of Chaff loaded in mortar shells to indicate to friendly radar sets the position of the front line. This development was initiated in ETO but was later transferred to development agencies in the United States.

The only known example of active RCM carried on in support of ground forces is one in which the cooperation of the Air Forces was requested to jam the enemy tank communications by flying over the battlefield equipped with special jammers. Special aircraft of the Eighth Air Force were employed for this mission. American-built ART-3 jammers were originally employed but British sets of the Jostle were used in the last part of World War II. During the battle of the Ardennes, a number of tank jamming missions were flown. The characteristics of these f-m jamming signals were such that the German a-m tank equipment was fairly easily jammed, whereas the American tank sets operating in the same bands with well-designed f-m receivers could operate satisfactorily through very heavy jamming. During these operations, little interference was experienced by the American tanks, whereas evidence exists to indicate that German tanks underwent serious jamming.

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Chapter 15

RCM IN THE PACIFIC THEATERS OF OPERATIONS

15.1 INTRODUCTION

THE KEYNOTE of the RCM program in the Pacific Theaters of Operations was that of investigation, as contrasted to the program in the Mediterranean and European Theaters of Operations. Offensive countermeasures were not employed until the early fall of 1944. At the start of World War II, Allied knowledge of Japanese radar was nonexistent, and, before a countermeasures program could be planned, a great deal had to be learned about the types of equipment and the operational tactics employed by the Japanese.

15.2 THE JAPANESE RADAR AND ITS OPERATIONAL IMPORTANCE

It was not until August 1942 that it was positively known that the Japanese had radar. At that time, in the invasion of Guadalcanal, a Japanese radar set was captured. This was a Mark I Model 1, intact. In the spring of 1943, searches conducted by Ferret I, in the Aleutians, confirmed the existence of two Mark I Model 1 radars on Kiska. These two sets and a similar one at Wake Island had, however, been first discovered by aerial photography. Early in 1944, Ferrets in the Southwest Pacific Area [SWPA] confirmed the use of 75-mc, 100-mc, 150-mc, and 200-mc early-warning [EW] radars in the region of the Admiralty Islands and Hollandia. Captured documents revealed that the SCR-268 and the SCR-270, as well as the British gun-laying [GL] Mark II and searchlight control [SLC] had been compromised during the Japanese advance into the Philippines and down the Malay Peninsula. Thus it was relatively certain that by the end of 1943 the Japanese radar art was comparable to that of the Allies in 1941.

Evidence of German-Japanese liaison existed, for example, in Japanese notebooks found at Hollandia, New Guinea, in which detailed summaries of the German Air Force radar jamming policy were given. It was certain that the Japanese knew, in August 1943, of the use of Window by the RAF during the historic Hamburg raid in July 1943. Later information revealed that the enemy also knew the characteristics of the British ground-controlled interception [GCI], aircraft interception [AI], air-to-surface vessel [ASV], H2S, and, in addition, had at least a superficial knowledge of Allied identification friend or foe [IFF] and tail warning receivers. Submarine searches in the Nanpo Shoto and Nansei Shoto chains and around the southern coast of the home islands of Japan revealed a well-developed radar net, although at that time it was impossible to judge the efficiency of their operation. In the summer of 1944 the 20th Bomber Command searches in the China-Burma-India [CBI] Theater and over the island of Kyushu revealed the same types of EW radar that had been found in other Pacific areas, and analysis revealed very complete EW coverage over occupied China. Intelligence information indicated that the Japanese were working on 10-cm air-warning radar for both land-based and ship-based applications. In the spring of 1945, a number of intercepts of suspected Japanese 10-cm radar were made over the home islands of Japan and in the Formosa area; however, in general, these radars were sporadically operated, and no widespread use of land-based 10-cm radar by the Japanese was ever confirmed.

It was known that the Japanese had airborne radar of the ASV type, operating on 150 and 200 mc. The ASV, Air Mark VI, operating on 150 mc, was used extensively by the Japanese in attacks on U. S. naval units. The Ferrets operating over Formosa made a number of intercepts in the frequency range 500 to 520 mc, which corresponded to that of Japanese airborne radars described in captured documents. These were suspected of being a type of AI radar, possibly adapted from the German Lichtenstein. Signals in the frequency range 1,000 to 2,000 mc were intermittently heard over the Japanese home islands and, in similar fashion, those around 1,100 mc corresponded with the

information in captured Japanese documents. No definite evidence was ever obtained that these signals actually emanated from enemy aircraft or that they were used for the purpose of aircraft interceptions.

The existence of ship-based radars had been revealed in captured documents and numerous intercepts were made during engagements with enemy naval units. These radars, operating on 150 and 200 mc, were used for air-warning purposes. There were also indications that the Mark IV Model 3 had been adapted for ship-board searchlight control. Captured documents had revealed that work was progressing on an adaptation of the German Wurzburg for ship-based operation, and several signals were intercepted around 650 mc during the shelling of the Mindoro beachhead by a Japanese task force. A CincPac report mentioned the interception and jamming of a signal at 606 mc near Zamboanga in the summer of 1945. It was also known that the Japanese had installed the Mark II Model 2, 10-cm surface-search radar, on ships; and its presence was first noted by interference on the indicators of 10-cm U. S. naval radars. Its characteristics were later

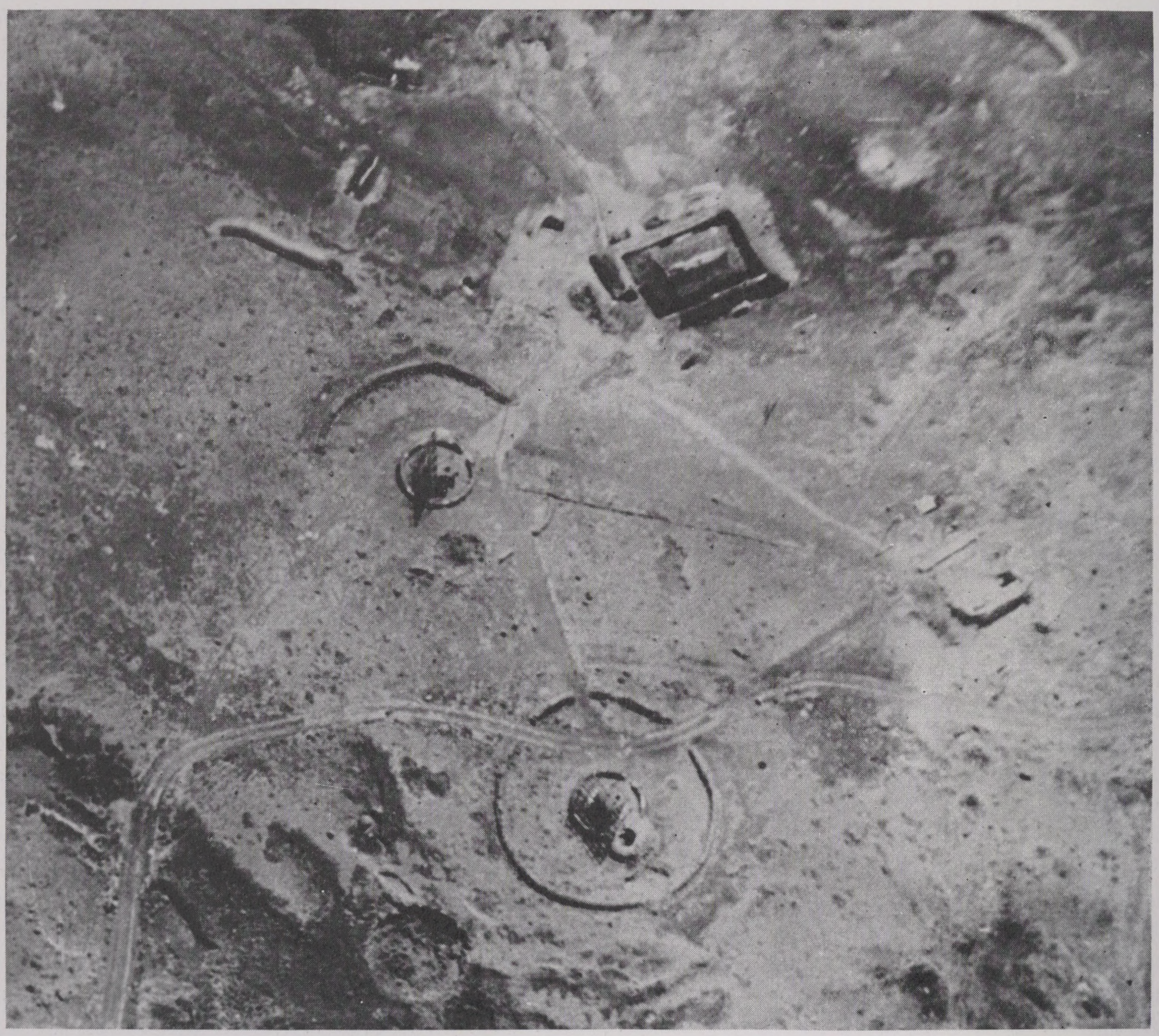


FIGURE 1. Aerial photograph showing dual installation of Japanese early-warning, Mark I Model 1 type radar immediately behind the main camp area at Kiska. Note the near miss of one bomb crater.

verified by signal intercept and analysis. An adaptation of the Mark II Model 2 for surface fire control appeared but never proved effective. Direction-finding [DF] work indicated that a 70-mc radar, having characteristics similar to the Mark CHI land-based radar, was being used on picket boats. Intercepts also revealed that the 28-mc SE radar and the Mark III doppler radar were being used on picket boats to a very limited extent. A lightweight radar was found which operated on 375 mc and which was to be used on suicide assault boats for directing attacks at night.

Captured documents had revealed the existence of Japanese GL and SLC radar, copied for the most part from American and British sets captured in the early days of World War II. An SLC radar, the Mark IV Model 3, was captured on Saipan in June 1944, and a Mark IV Model 1 was captured on Peleliu in September 1944. In October 1944, 5th and 13th Air Force units had gathered sufficient evidence to establish the existence of 200-mc radar in the Balikpapan area, having characteristics which indicated that it could be used for gun laying. Units of the 5th Air Force also intercepted 200-mc GL signals in the Clark Field area on Luzon and 75-mc GL signals on Takao, Formosa. In February and March 1945, a large number of intercepts at 75 and 200 mc were associated with flak and searchlight activity by 21st Bomber Command units over the home islands of Japan. No definite intercept of a signal having Wurzburg characteristics was ever made over land. In only one instance was a 10-cm intercept ever associated with flak and this was probably pure coincidence.

Thus, the Japanese were seen to have crude, but effective, EW radars in quantity. The EW coverage in the Southwest Pacific Area was far from complete because of the relatively few radars available and the large distances between islands; coverage gaps were further augmented by U. S. efforts to destroy particular sites. In the CBI Theater, enemy EW radar coverage was extensive, and, since the B-29 raids across China had to follow a prescribed course at high altitude, it was considered impossible to avoid the EW net. In the Western Pacific, the EW net in the Nansei and Nanpo Shoto chains was elaborate but susceptible to deception and destruction. Early-warning coverage for the southern coast of Japan was extremely good and the concentration of radars and the diversification of frequency made deception or destruction of individual installations unprofitable.

By the end of 1944, Japanese airborne radar reached a technical level comparable to that of the Allies in 1941. It never constituted a problem to the U. S. Air Forces. It did, however, help the Japanese in shadowing U. S. Fleet movements and was often used to guide Kamikaze attacks; for both of these reasons it was a definite menace to naval operations. The few intercepts at 500 mc and 1,100 mc indicate that the Japanese were on the road to better airborne radars, particularly AI, and their use might have developed into a serious problem for the Air Forces.

Ship-based radars were, for the most part, dual-purpose sets, comprising the design character of both surface-search and fire-control equipment. By changing the pulse width and repetition frequency, the enemy attempted to transform his radar magically from one purpose to another. The result was a mediocre search set and a very poor, almost useless, fire-control system. In spite of this fact, a few cases are on record of the enemy's ineffective attempt to utilize ship-borne fire-control radar. A 650-mc set may have had possibilities for surface fire control, but it never passed the experimental stage.

Japanese land-based fire-control and searchlight-control radars, admittedly four years behind Allied developments, were instrumental in permitting the Japanese to shoot down our aircraft under unseen conditions. As such, they constituted a serious Air Force problem.

The Japanese themselves understood that their radar was inferior to that of the Allies and sought to present flimsy excuses to their people. For example, an article in the January 1944 issue of *Manichi Shimbun* said: "The point where our electrical weapons are surpassed is not in design but in manufacturing technique . . . the glass porcelain, filling materials, filament, etc., are of lower quality and the life of the valve is short."

SECRET

15.3 THEATER ORGANIZATION

For the purposes of this report, the Pacific Theaters of Operations are subdivided into the following areas: The Northern Pacific; the Southwest Pacific; the China-Burma-India; the Central and Western Pacific. In the Northern Pacific Area, radar countermeasures [RCM] activities were carried on by the Eleventh Army Air Force, Army Ground Force units, and naval air and sea units of the Eleventh Fleet. The Fifth and Thirteenth Army Air Forces, Army Ground Force units, and the Navy Seventh Fleet were engaged in RCM operations in the Southwest Pacific Area. The RAAF also carried on a small-scale RCM effort in the Southwest Pacific Area, but their activities will not be considered here. In the CBI Theater, the Twentieth Bomber Command of the Twentieth Air Force, the Tenth Air Force, and the Fourteenth Air Force were engaged in the investigational phases of the RCM program. In the Central and Western Pacific Areas, the Seventh Army Air Force, the Twenty-first Bomber Command of the Twentieth Air Force, and units of the Third and Fifth Fleets were all engaged in RCM activities. The RCM organization within each theater is discussed briefly in later sections.

15.4 U. S. CIVILIAN AID TO THE ARMED FORCES

Twenty civilian technical observers or scientific consultants were supplied to the Pacific Theaters of Operations by the Radio Research Laboratory [RRL] of Harvard University. In the Pacific, there was never a completely civilian laboratory, similar to the American-British Laboratory of NDRC Division 15, and, in general, civilian personnel were assigned directly to the air force or theater headquarters which requested their services. A civilian technical observer accompanied the Beaver I mission to the Aleutian area and advised in the technical and operational phases of its activities. Ferrets VII and VIII were accompanied to the Southwest Pacific Theater by two technical observers and, throughout the period of operation of these Ferrets, at least one civilian was assigned to the organization controlling their operation. Section 22 of General Headquarters, Southwest Pacific Area, at one time had as many as six scientific consultants attached to its RCM staff; the majority of these were assigned to the Fifth and Thireenth Air Forces to aid in their installation and operational program. The 20th Bomber Command (the first operational unit of the global 20th Air Force) had assigned to it two technical observers, who reached the CBI Theater before the Twentieth Bomber Command began operations. One of these two was subsequently assigned to the Fourteenth Air Force and aided in the outfitting of the interim Ferret for that air force. Technical observers remained on duty with the Twentieth Bomber Command until it moved to the Marianas. At various times, civilian scientific consultants were attached to Headquarters, United States Army Forces, Pacific Ocean Area, Hawaii, where they aided units of the Army Ground Forces, Army Air Forces, and Pacific Fleet in the Hawaiian area. A civilian technical observer was attached to the Twenty-first Bomber Command of the Twentieth Air Force and accompanied it overseas to the Marianas; he advised on its operational and installation program throughout the nine months of its existence.

15.5 NAVAL RADAR COUNTERMEASURES

15.5.1 Organization

The Naval RCM Problem in the Pacific

In the Atlantic and European Theaters, the Navy's radar countermeasures problems were concerned with two very specific situations: convoying; and supporting amphibious landings. Information concerning German radar developments was plentiful and definite, due to proximity and wide-spread German use, and, therefore, the requirements for radar countermeasures were equally definite: (1) convoys had to be provided with a radar-countermeasures team capable of intercepting and locating enemy U-boat radars when used; (2) during amphibious landings radar-countermeasures teams had to be provided capable of jamming enemy coast-watcher and gun-laying radars for the protection of amphibious forces during the actual landing operations. In this latter case all available radar counter-measures material and personnel could be concentrated for the landing involved and then shifted to cover the next

operation. Because of the above considerations, plus the fact that much of the necessary preliminary intercept and intelligence information was already provided by the Army and the British, a few small Navy radar-countermeasures expert teams were found most efficient for operation in the Atlantic and European Theaters.

In the Pacific an entirely different state of affairs existed and required radically different approaches and solutions. In the first place, as late as the middle of 1942, practically nothing was known about Japanese radar developments. This was due to a second factor—the tremendous distances involved in the Pacific. In fact, it was not until after the Marines had captured an early model Japanese radar on Guadalcanal and when it became possible to project radar intercept equipment mainly by plane and submarine into Japanese controlled areas, that sufficient information about Japanese radars became available to permit initial planning of jamming equipment. Another factor was the difference in the state of radar development in Japan and Germany. The Germans were well advanced both in quality and quantity of equipment over the Japanese which at once was a curse and a blessing from the point of view of Pacific radar countermeasures. The legitimate needs of the European Theater to counter an immediate enemy radar threat left few personnel and little equipment for the Pacific. On the other hand, until 1943, there was little need for more than "watchful waiting" in radar countermeasures in the Pacific.

However, by the fall of 1943, the Japanese had a rather extensive radar net in operation and the value of the exploratory work being performed by the few radar countermeasures teams became increasingly apparent. By the summer of 1944, this radar net had reached the point where it constituted a genuine threat to our forces; it was immediately obvious that a change in concept was in order. Pacific operations spread over a vast expanse of ocean and islands and one might encounter enemy radars—shore, ship, submarine and airborne—at any point and any time in this immense area. Also, one "D-Day" followed closely on the heels of another; it became impossible to transport radar countermeasures material and personnel rapidly enough to fill the needs, and there was no guarantee of having them when and where they were needed. Even when offensive operations were not in progress, there was never enough information on Japanese radars—types, locations, and uses. To fill these requirements, radar countermeasures was taken out of the "special team" category and integrated with the fleet radar and CIC programs. As more and more equipment became available it was spread throughout the surface fleet, submarines, and air force from the Aleutians to the Marshalls, from Pearl Harbor to Okinawa, until at the end of the war, radar countermeasures had become a fleet-wide proposition taking its place alongside and supplementing radar—the weapon it served to deny to the Japanese and whose every use on their part worked only to their own detriment. In this status it is today, and will remain—a full-fledged weapon of the fleet.

Inception of United States RCM Effort

Shortly before December 7, 1941, it became apparent to several of the electronics officers in the Navy Department in Washington, that our rapidly expanding development and application of electronics devices to warfare would require an aggressive program of countering similar devices which would be used by our enemies. Within a few days after the Pearl Harbor attack, a meeting was called at MIT at the suggestion of one of the Navy bureaus to enable Service representatives to discuss the general problem of countermeasures equipments, techniques, etc. At a subsequent conference held in the Navy Department, it was decided by NDRC that a new laboratory should be established to handle this work rather than overloading the already overworked staff at the Radiation Laboratory.

Out of these conferences grew the Harvard University contract for the establishment of the Radio Research Laboratory. Some countermeasures work had been done, however, by NRL prior to the establishment of the NDRC facility and the work at NRL expanded during the war and supplemented the efforts in this field put forth by NDRC.

RCM in the Navy Department, Washington, D. C.

The Navy Department Countermeasures activities were centralized by a countermeasures group established under the Director of Naval Communications, and the establishment of the Countermeasures Section in the Radio Division of the Bureau of Ships and a Countermeasures Desk in the Radio and Electrical Section in BuAer provided focal points in the two bureaus for the coordination of countermeasures activities and the active development of countermeasures equipments. The unusual nature of the electronics countermeasures problem made it essential to maintain extremely close liaison between the development laboratories, the tactical organizations in the theaters which use electronic equipments, and intelligence and other information groups which provide information concerning enemy electronic systems in use or projected which must be countered. There was also a need for very close coordination between the branches of the Services and the development laboratories concerned with the problem. As a result of this need, the Joint Countermeasures Committee was established by the Joint Communications Board of the Joint Chiefs of Staff during the summer of 1942. The representative of the Director of Naval Communications was elected chairman of the committee. This committee functioned very effectively to maintain coordination and an aggressive, cooperative spirit among the several interested branches of the Army and Navy and with the NDRC research laboratories.

RCM in the Fleet

Originally countermeasures officers and men with training in radar countermeasures, communication

SECRET

countermeasures, and anti-jamming methods arrived in the Pacific Theater grouped into teams. It was found expedient, however, to assign the officers and men either individually, or in smaller groups later known as "Functional Components." By 1 September 1944, the Navy personnel situation was as follows: a number of Functional Components were formed under ComDesPac, ComSubPac, ComNorPac, and COTCPac and employed to man RCM equipment during fleet operations and for training purposes between operations. In addition, fifteen graduates of the Applied Communications Course at the Post Graduate School, USNA, with additional countermeasures training had been assigned to key

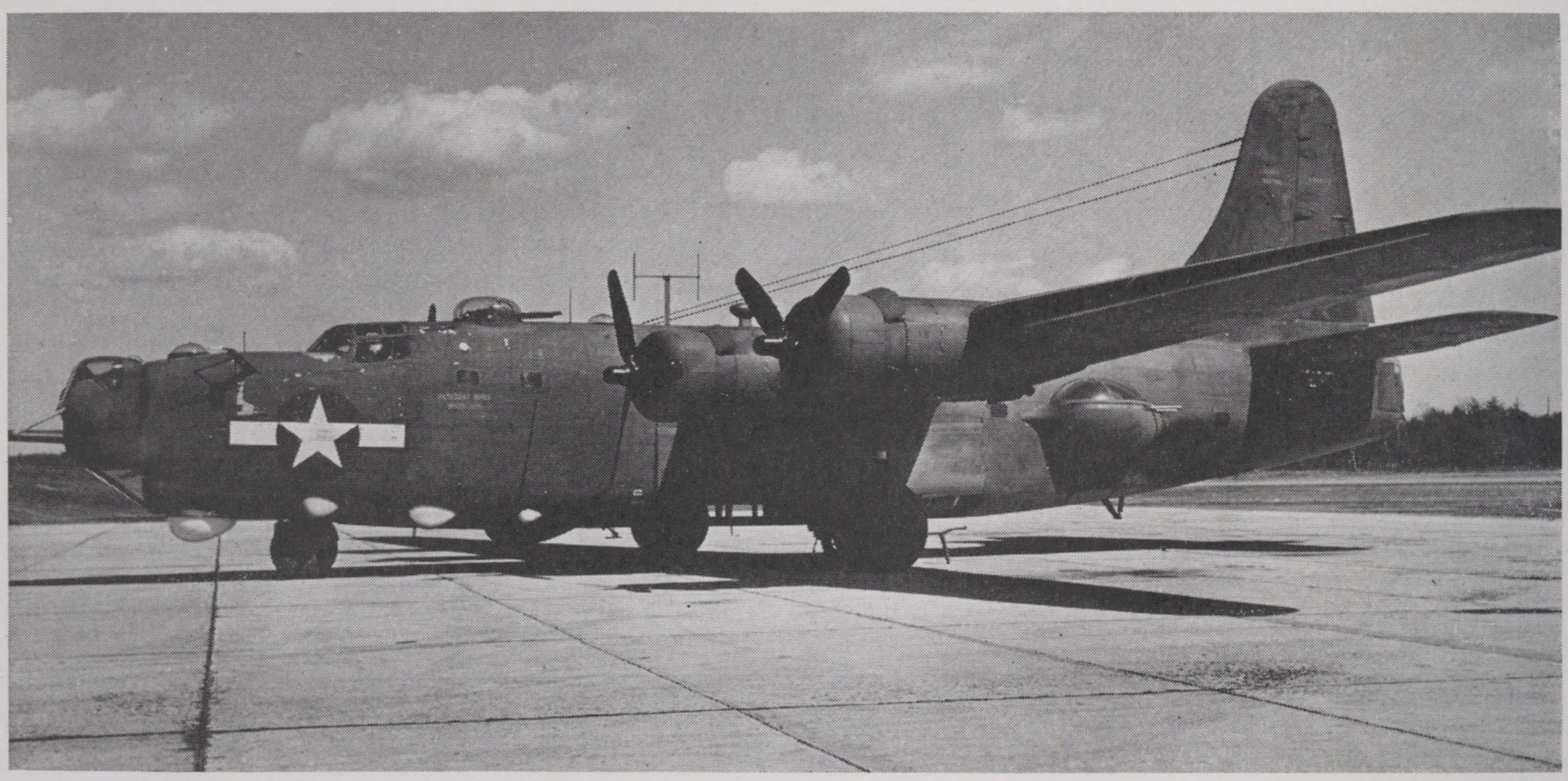


FIGURE 2. RCM antenna installation on PB4Y-2 long-range naval patrol bomber.

Navy staffs to advance the fleet countermeasures program in its earlier stages.

In each of these "key Navy staffs" (CincPac, ComNorPac, ComSouWesPac, Com Eleventh Fleet, Com Seventh Fleet, Com Third Fleet, and Com Fifth Fleet), RCM was destined to play a major role.

By the beginning of 1945, when RCM was put on a fleet-wide basis, a new personnel plan was necessary. As evidenced by the paragraph below, countermeasures transcended, at that time, the role of an electronic specialty:

> Although GMCM, CCM, and a limited number of RCM assignments will be handled by specialists, shipboard RCM duties will be performed by our ships' radar and CIC personnel. Training in RCM is now given to radar operators, radio technicians, CIC watch officers, radar material officers both in mainland schools (including the course in Applied Communications, Post Graduate School, USNA) and at the Pacific Fleet Radar Center. Personnel aboard ships without early availability at Pearl Harbor can receive RCM instruction from forward area training teams and groups. It should be noted that specialized RCM personnel as such are not ordered to individual ships for permanent duty; their radar and CIC personnel should take advantage of one of the above-mentioned training courses depending upon the nature of the ship's availability.

The formal training of countermeasures personnel first received attention in December 1942 when Op-20-S-2 in VCNO formulated a training plan and queried staff commanders such as CINCPAC, CincLant, Com Third Fleet, and Com Seventh Fleet about the desirability of attaching officers with such RCM training to their staffs. General concurrence was received and the first two groups of officers were assembled for training in January 1943; after a seven weeks' course at the Special Projects School, Anacostia, Maryland, they departed for duty. (One of the 7 weeks was spent at the Radio Research Laboratory, Harvard University.) Slightly later, a special projects school for air was set up in conjunction with BuAer, Op-33, and Op-31. In addition to the above Stateside training facilities, several RCM schools were established in the Pacific. For example, at Pearl Harbor there was the Fleet Radar Center, with auxiliary groups in ComDesPac, ComSubPac,

SECRET

and ComAirPac. At least twice a week these training activities sponsored the use of electronic jammers and various forms of Window against Hawaiian radar defenses. In the critiques which followed each exercise there was an opportunity to evaluate the tactical merit of numerous RCM plans. In addition, valuable lessons were learned by the operators of both the radar and the countermeasures equipment.

To supplement the RCM education of staff and operating personnel, two books had been published by March 1943, the first known as *Radio and Radar Countermeasures,* CSP 1765 (a), and the second, *Black Magic,* CSP 1772 (A). Later on, fleet education was supplemented by films prepared in the Bureaus, Naval Research Laboratory [NRL], RRL, and the Joint New Weapons Committee [JNW]. In addition, RAD-7, *Operators Countermeasures Manual,* and RAD-12, *The Airborne Countermeasures Operators Manual,* were prepared as textbooks under the direction of COMINCH.

In retrospect, the Navy installation program is seen to fall into three categories: stopgap, interim, and ultimate. The first category involved prototype equipment installed in surface vessels by a specialized team after the vessel was under way toward an enemy objective. Such a procedure was followed from August 1943 until the spring of 1944. At that time, interim installations of production-line intercept receivers and l-f jamming transmitters were begun mostly on the smaller vessels. Ultimate installations with the elaborate RCM equipment allowances started in the first part of 1945.

The tactical plans, policies, and doctrines governing the use of radar, radio, and guided missile countermeasures in the U. S. Navy were consolidated for the first time at the end of 1944 in Cent Com Two, Annex B; as the use of RCM equipment expanded, this document was periodically revised and supplemented. Similar material, revised to April 1945, is contained in PAC-70 (B), *Radio and Radar Countermeasures and Deception.*

15.5.2 Investigation

The foremost problem in naval countermeasures operations was one of securing intelligence on enemy radar. Since this problem continued throughout the length of World War II, the sources of such intelligence were carefully developed to include

1. Interference on U. S. radar.
2. Use of intercept receivers, analyzers, and DF antennas.
3. Captured equipment.
4. Captured documents.
5. Prisoners of war.
6. Agents.
7. Aerial photographs.
8. Periscope inspection.
9. Radio interception and analysis.
10. Deductions from the analysis of combat operations.

Each of these various means was, at one time or another, used by U. S. naval forces to determine the quality, quantity, disposition, and operational usage of Japanese radar. For a detailed account of the information gained, one may consult two publications, *Japanese Shore-Based Radar Locations* and *Japanese Radio and Radar Equipment,* which were prepared by the Radar Countermeasures Section of the Commander-in-Chief, U. S. Naval Forces in the Pacific. It is interesting to note that by October 1944, when Japanese airborne radar offered the first serious threat to U. S. naval operations, sufficient information was available to permit the successful use of offensive radar countermeasures.

Perhaps the first contact with Japanese radar came on November 6, 1941, before the outbreak of hostilities. The USS *Chester,* proceeding in slow convoy with two Army transports near the Marianas, made radar contact with an unidentified vessel. Interference was noted on the A scope of the *Chester's* newly installed CXAM, a 200-mc search set. In the absence of other radar, the interfering radar signal, which appeared to be variable in frequency, pulse length, and repetition rate, was believed to originate on the unknown vessel, tentatively identified as a Japanese destroyer. Needless to say, such information was inconclusive and offered no concrete basis for the future planning of countermeasures equipment.

By December 1941, an American intercept receiver known as the P-540 had been success-

SECRET

fully flown over Germany; the British had ordered approximately a hundred, and on December 22, 1941, it was pointed out that such intercept gear was a prime necessity for U. S. investigations in the Pacific. The Naval Research Laboratory began work on a crystal or diode detector-type receiver, later to be known as the XARD, while the Radio Research Laboratory of Division 15, NDRC, undertook to improve the design and increase the frequency range of the P-540, a superheterodyne receiver with plug-in tuning units.

As search receiver development continued in the United States, far-ranging Navy submarines with 114-mc SD radars encountered numerous cases of interference. The first of these reports came in December 1942, off the atoll of Truk; such information correlated reasonably well with the measured characteristics of an enemy Mark I Model 1 search radar captured at Guadalcanal.

Thus, the first year of the Pacific war netted only a small amount of information on Japanese radar. It was firmly concluded that the Japanese were cognizant of radar techniques and had developed EW-type radar prior to the outbreak of hostilities. Such sets as the Mark I Model 1 were known to operate from 92 to 108 mc for purposes of land-based air search. Japanese ship-borne and aircraft radars were suspected but not proved. No radar jamming or deception had been tried operationally by either side. By comparison, the investigational phases for Japanese communications had progressed tremendously because conventional l-f, ground-based receivers could monitor distant transmissions.

Search receiver development, progressing at high priority in U. S. laboratories, had reached the stage of prototype equipment for the lower-frequency ranges, 40 to 300 mc, by January 1943. A sample quantity of receivers, XARD and ARC-1 (the outgrowth of P-540), were prepared for installation in aircraft, surface vessels, and submarines. The Army Ferret I, destined for radar reconnaissance of the Aleutians, received one of each equipment, as did a Navy PBY operated by Section 22, General Headquarters, Southwest Pacific; the balance, no more than ten, went aboard naval vessels.

By March 1943, two more Mark I Model 1 radars had been captured in the invasion of Attu. Ferret I's radar reconnaissance of the Aleutians had been completed and the dual radar installation above the main camp area at Kiska Harbor was sufficiently well known that offensive RCM operations could be planned. The Beaver I mission, organized to counter specifically these two sets, enjoyed the assistance of one Navy officer and four Navy enlisted men, in addition to RCM personnel detached from the staff of ComNorPac.

In the south and southwest Pacific, by the use of prototype intercept receivers, a total of 34 different Japanese radars had been reported by June 1943. These radars, according to intercept information, extended from 100 to 740 mc, with noticeable concentrations at 100, 150, 200, 300, and 700 mc. Evaluation of these first reports was a tedious and uncertain job, because the ARC-1 offered many spurious responses and knowledge of friendly radar characteristics was not widely spread within our own forces.

Up to this time, radar intelligence had come primarily from captured equipment, captured documents, and aerial photographs. Here for the first time, then, we find a sizable increase in our knowledge of the enemy's radar defense by the use of flight intercepts. Ship-borne receivers were to produce worth-while intercepts a short time later in August 1943.

In summarizing naval intercept operations up to the end of 1943, it is seen that captured documents, captured equipment, aerial photographs, and airborne and ship-borne intercepts were the principal sources of U. S. knowledge of Japanese radar. At year's end, 14 land-based, EW search radars had been definitely located in the Southwest Pacific Area. The number of different enemy radar intercepts was approaching one hundred. The existence of Japanese ship-borne or airborne radar was still not definitely proved, though documents had been found referring to 200-mc ship-borne equipment of the EW type. No offensive countermeasures had been employed by U. S. naval forces.

Investigation by Naval Aircraft

Investigation and intercept to determine the

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quality, quantity, disposition, and operational usage of Japanese radar was undertaken by tender-based, land-based, and carrier aircraft. The earliest operations of this kind utilized land-based aircraft with prototype search equipment. As mentioned in the above paragraphs, a B-24, known as Ferret I, and a Navy PBY started operations in the early spring of 1943, in the Aleutian and Southwest Pacific



FIGURE 3. Typical PB4Y-2 RCM installation. Reading from left to right are: top shelf—1 AN/APT-1, 1 AN/APA-10; middle shelf—1 AN/APA-11, 1 AN/APA-17; bottom shelf—1 AN/APT-5, 1 AN/APR-1.

Areas, respectively. Although both of these aircraft were under the immediate operational control of the Army, they drew heavily on prototype equipment developed under Navy sponsorship. Although the supply of intercept receivers was still in short quantity, in September 1943

planes flying under Admiral Halsey's command in the South Pacific commenced regular search operations to intercept, locate, photograph, and bomb out Japanese radar installations. . . . In addition to the regular searches, [these] planes were kept continuously on station night and day in and above the upper Solomons to detect Japanese shipping. Any such ships using their radars were spotted by the radio-countermeasures equipment in these planes and reports made of their presence thereby. In addition, this equipment was used to tell if the planes themselves had been detected by the Japanese radars; if such were the case, position was quickly changed, since planes and trained flight crews were at a premium in the "shoestring" days of 1943.[852]

In November of 1943, radar-countermeasures-equipped "Black Cats"—Navy night-flying PBY's—commenced similar operations under the Southwest Pacific Area command and, together with Army "Ferrets," located, studied, and bombed Japanese radar in that area.[852]

By the beginning of 1944, the broad strategy for future Pacific operations had been crystallized. As an adjunct to the numerous landings which were planned, United States carrier forces were asked to carry out raids deep in enemy waters. For example, Central Pacific carrier forces had selected highly touted Truk in the Carolines as their first target. Target data were required, since no previous reconnaissance of this enemy base had been conducted. It was decided that aerial photographs might be obtained by Marine photo-reconnaissance planes flying from advance bases. To assist the protection of these photo-reconnaissance aircraft, as well as to obtain radar reconnaissance information for later uses, an RCM investigation was scheduled as the first move in the operation. The first flight, then, was made by land-based naval patrol bombers which took off from Munda and refueled at Bougainville.

With belly tanks so full of fuel for the long hop to Truk and back that the bomb bay doors couldn't be closed for 300 miles, they flew over and around the "vaunted and impregnable fortress" charting the coverage of the various Japanese radars. Based on the information brought back from this radar-countermeasures flight, the Marine photo-reconnaissance planes approached Truk in a blind sector of the Japanese radars, took their pictures and left before the unalerted Japanese were fully aware that the planes had been overhead.

The preliminary radar investigation of Truk was put to such excellent use by the Marine aircraft that additional investigations were ordered for later use by carrier and other forces. The task was assigned to VPB 116, a

SECRET

squadron of PB4Y aircraft then operating from Eniwetok. A report on these missions is quoted here in the words of Commander Donald G. Gumz.

> We did use it (RCM) when we got forward, to conduct a radar survey of enemy radar facilities in Truk. ComAirForwardArea at the time asked us to locate enemy radar equipment on Truk and attempt to pinpoint it. Unfortunately, the Japanese transmitters they were using there most effectively were between 98 and 105 mc, I believe, and it was very difficult for us to get any kind of bearing with our equipment, on a transmitter on that frequency. Consequently, we had to think of something new. The plan required about six night sorties up in that area with the three RCM planes searching for holes in their screen at varying altitudes. We ran three concentric circles around Truk lagoon, one at around 2,000 feet altitude, and staying just outside their range. We'd come in and they would pick us up, and then we'd drop back out again. Using our George gear, to keep our position accurately pointed, we got a circle at 2,000 feet. It had holes in it where we could approach closer. Then we went in at a thousand feet and did the same thing for a thousand foot circle. And then we closed in to a 500 foot altitude vs. intercept circle. We noted that consistently there were spots opposite certain islands and projections that would permit us to close considerably inside that outer circle at that altitude, and they all pointed towards a plateau on Moen. So one morning we went inside the lagoon, primarily on a shipping strike at low level and saw no shipping but did pick up some interesting information. As soon as we got inside the shadow of Moen, the 98-105 mc radars that had been following us all the time lost us. Once inside the reef, it turned out that they couldn't depress the antenna and follow us, but we did pick up a 300 mc which was a very strange frequency to us then, and another odd frequency, 198 mc, I believe, picked us up immediately and started following us again. Well, naturally we expected a rather hot reception knowing that we had been on their screen for some time (15 minutes before we crossed the reef line), and we were always very much amazed that there were no fighters airborne when we got in. It wasn't until we had completely circumnavigated the lagoon and followed the shore line around Moen within 20 and 40 mm range and were on our way out, that they launched fighters. It was something that I have never been able to reconcile with the fact that their radar intercept of an approaching single airplane was excellent enough to pick you up at 50 feet altitude some 30 miles from the reef. Incidentally, their operators were very good. We could shake our own in the Oahu area, but we could never shake them, except by getting out of range. Those operations were the most interesting that we conducted out of Eniwetok at the time.

As a result of such searches, the succeeding carrier air strikes on Truk were planned in a way that assured the least reaction by Japanese aircraft and the greatest safety to U. S. carrier forces.

In August 1944, prior to the first Philippine operation, plans were laid for radar reconnaissance of Leyte Gulf, Manila, and other Philippine areas by a small number of TBM's. These same aircraft were also to be used for an investigation of the Palau group. Unfortunately, these plans were never carried out because several of the TBM's were destroyed before seeing action.

At approximately this same time, the installation of RCM equipment in naval aircraft was proceeding according to an interim program. A standard allowance of RCM equipment for the planes of each squadron of land-based naval aircraft had been established; for carrier aircraft, installations were made on the basis of the demands of a specific operation. Thus, by the end of August 1944, 18 squadrons of land-based naval patrol aircraft were operating in the Pacific, and in 13 of these squadrons, installations of the following equipment had been completed:

1 AN/APR-1,
1 AN/APA-6,
1 "Snooper" DF antenna,
1 Jamming transmitter (AN/APT-1, AN/APT-3, or AN/APQ-2).

In addition to these, installations of M-2300 (later known as AN/APA-17) were made in one plane each of squadrons VPB 102, 116, and 117. One AN/APR-5 was installed in one plane each of squadrons VPB 146 and 150.

As operations continued, airborne intercepts were of greater and greater value; as early as the fall of 1943, long-range planners in the Bureau of Aeronautics were moved to include a formidable RCM installation in the Navy's new land-based search aircraft, the PB4Y-2. By mid-1944, search operations had so confirmed their conclusions that additional RCM equipment was authorized for the PB4Y-2. This aircraft, similar to a B-24, though modified by adding 7 ft to the fuselage and utilizing a single tail, was to be equipped with

1 AN/APR-1,
1 AN/APR-2,
1 AN/APR-5AY,

1 AN/ARR-5,
1 AN/ARR-7,
1 AN/APA-6A or AN/APA-11,
1 AN/APA-17,
1 AN/APA-24,
1 AN/APA-10,
1 AN/APT-1,
1 AN/APQ-2,
1 AN/APT-5.

All of the above equipment was not intended for use at the same time. Standard mounting racks allowed for the interchange of intercept, analyzing, and jamming equipment depending on the nature of the mission.

Carrier aircraft, following suit in October-November of 1944, adopted a similar ultimate installation plan with equipment allowances of

5 AN/APR-1,
5 AN/APA-6,
5 AN/APT-1,
5 AN/APQ-2,
5 AM-14/APT,
5 AM-18/APT,
2 AN/APR-5AY,
2 AN/APR-2,
2 AN/APA-10,
2 AN/APA-23.

This equipment was placed aboard CV's and CVL's to permit RCM installations in five TBM's or TBF's per carrier.

Each squadron of multiengined land-based naval aircraft (other than PB4Y-2's) was authorized to equip three planes with the following RCM equipment:

1 AN/APR-1,
1 AN/APA-6 or AN/APA-11,
1 "Snooper" direction-finding antenna,
1 AN/APA-17,
1 AN/APA-23,
1 AN/APQ-2.

The tactical doctrine controlling the use of this large quantity of equipment was formalized in Cent. Com. Two, Annex B, and later PAC-70 (B), at the same time that the ultimate installation program got under way. With regard to the investigational phase of radar countermeasures operations, a generalized plan such as the following was adopted.

1. As many carrier aircraft as practicable should be furnished with RCM intercept equipment and should accompany the first strike on any specific target area or on a large task force to determine the extent and effectiveness of enemy radar activities and to spot any previously unreported enemy radar frequencies. Subsequent strikes should be accompanied by at least two RCM-equipped planes to insure that no new radars are placed in operation on different frequencies. This RCM intercept information should be used to determine the length of Window to be dropped and the settings to which jammers should be pretuned.

2. Shore- or tender-based air squadrons should maintain a continual RCM survey of enemy objectives. The fleet commanders may order detailed additional searches of any specific enemy location they feel warrants such treatment.

In addition to the above, shore-based air squadrons should make maximum use of their RCM intercept equipment for evasive tactics (flying around or under radar beams or coming down a null) and for homing purposes, to permit bombing and strafing of enemy radar locations, and to obtain all possible information concerning enemy electronics to guide research and development agencies. In so far as practicable, all bombing and search missions should include at least one RCM-equipped plane.

Thus, by the beginning of 1945, with the ultimate installation program proceeding at a rapid rate and the fleet-wide adoption of Cent. Com. Two, Annex B, as a consistent policy, doctrine, and plan for the use of RCM, airborne radar investigations reached a climax at the time United States forces were operating most closely to the heavily defended shores of the enemy home islands. Shore-based search aircraft continued to contribute to our knowledge of enemy radar by performing the task which they pioneered. Carrier-based air intercept operations followed suit on a somewhat smaller scale. In particular, night carrier air operations were quick to realize the benefit of airborne intercepts. For example, the RCM officer of Night Carrier Air Group 90, based on the USS *Enterprise,* made this evaluation of airborne intercepts at the conclusion of operations against enemy targets on Kyushu and the Inland Sea, March 18-20, 1945.

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It is believed that some emphasis should be made on "Ferret" flights. It is highly necessary to detect new enemy frequencies; to observe operating techniques; to pin-point stations. Sometimes this work can be done during regular scheduled flights (especially search missions) without interfering with the primary mission of the aircraft. This was done by Air Group 90 in the South China Sea and on Heckler missions around Kyushu and the Inland Sea of Japan.

The nature of some flights, such as the strike missions in the Bonins, make it hard to do much intercept work. There the flight to the objective was of short duration. The aircraft would orbit at a designated position before making individual runs on the target. Then evasive tactics were used while getting away from the target, and proceeding to a rendezvous point more orbiting would be done. The operator, as a rule, would lose track of his location and therefore very few good fixes were obtained. It is believed that the primary purpose of RCM personnel and equipment on strike missions should be to give the aircraft as much protection against FC/SLC radar and radar-equipped enemy aircraft as possible . . . Therefore, if strike missions are being sent out and RCM reconnaissance is needed, special flights should be made, if possible. In addition, when in enemy waters, a good RCM intercept watch can be made while on a routine anti-submarine patrol. It furnishes an excellent chance for an operator to gain experience and also makes valuable intercepts.

In the succeeding months, intercepts by U. S. naval aircraft contributed to the effectiveness of each amphibious operation. A detailed account of these later operations, given in the subsections entitled "Aircraft" under Sections 15.5.3 and 15.5.4, reveals the extent to which U. S. naval forces relied upon the use of airborne intercepts. In summary, it will be noted that naval airborne search equipment was used for the following purposes.

1. To intercept and identify the different types of enemy radar.
2. To determine the location of enemy airborne, ship-borne, or shore-based radar by the use of DF antennas.
3. To investigate the coverage of a given enemy radar site and to obtain information necessary for plotting radar shadow zones.
4. To intercept and analyze new enemy signals in order that effective jamming transmitters could be designed.

(From a careful analysis of the results of these four operations, the quality, quantity, disposition, and tactical usage of Japanese radar could be determined.)

5. To attack and destroy enemy airborne, ship-borne, and land-based radar.
6. To determine the exact instant of detection of an Allied aircraft by enemy radar and hence give warning of the need for evasive action.
7. To assist in determining the identity and location of friendly vessels.

Investigation by Naval Vessels

Intercept of Japanese radar from U. S. naval surface vessels or submarines was first attempted in August 1943.

In the days when the Pacific war meant holding a line in the South and Southwest Pacific . . . radar countermeasures had its start. The records show that the first crude radar countermeasures equipment—an intercept receiver—was installed in one of our submarines operating from Australia. The first war patrol of the submarine so equipped which produced worthwhile intercepts of Japanese radar occurred in August 1943.[852]

At about the same time, five radar intercept teams equipped with prototype search receivers and commercially manufactured audio oscillators and oscilloscopes for pulse analysis were ordered to the Pacific for employment aboard any vessels scheduled to participate in an early raid against the enemy. These teams, working under adverse conditions, were expected to report aboard a destroyer or cruiser and make their installations while the force was under way. When the attack was over, they could be moved to other vessels scheduled for attacks in different localities. This method of operation had been used with some success in the European Theater, but it very quickly became obvious that Pacific requirements could not be met by the work of five specialized teams.

In August 1943, then, the first of these teams with its makeshift equipment was placed aboard the cruiser *Montpelier* and functioned during the bombardment of Munda, prior to the landings. Japanese radars were kept under surveillance and valuable information forwarded to Washington to guide the design of suitably improved intercept equipment and jammers. In similar fashion, the other teams met with only moderate success in attempting to intercept enemy radar. The second team in-

stalled its equipment aboard a destroyer scheduled for participation in a carrier task force raid on Marcus Island. From August 27 through August 31, a continuous 24-hr search watch was maintained with an ARC-1 receiver, but no definite enemy signals were intercepted. Their efforts were not fruitless, however, since experience in this raid with friendly radar indicated the need for developing ship-borne DF antennas at radar frequencies. On September 18, 1943, the third and fourth teams participated in a carrier task force raid on Tarawa Atoll in the Gilbert Islands. One team was aboard a destroyer and the other aboard the cruiser *Minneapolis*. Reports from the cruiser team indicated that "by keeping a careful watch on the Japanese radars on the small islands, it was possible for our force to evade many of them and at the worst know the moment when surprise was no longer effective because of radar detection." Aboard the destroyer no enemy signals were heard. Again, however, valuable lessons were learned which guided the future development of fleet radar countermeasures. In particular, this team pointed out that:

1. Analyzing equipment to determine pulse-repetition rate and pulse length was an essential adjunct to the operation of an intercept receiver.

2. Spurious responses in the intercept receiver should be minimized or eliminated.

3. The characteristics of U. S. radar should be made available for interpreting intercept results.

4. Airborne radar could be intercepted at distances greater than 80 miles.

By the beginning of 1944, it was clearly understood that specialized intercept teams would not suffice to meet the operational RCM problems in the Pacific. An interim installation program was authorized in which smaller surface vessels and submarines were allotted one AN/APR-1 receiver and one AN/APA-6 pulse analyzer for permanent installation. The total volume of equipment was not large and the number of trained personnel barely sufficient. Thus because of

the drain on personnel and equipment for D-day in Europe, the Navy's radar countermeasures effort in the capture of the Marianas was held down to a slight extension of the procedures used in the Gilberts and the Marshalls. . . . The Palau operations in September, 1944, found our forces for the first time with sufficient men and material to make a coordinated radar countermeasures plan feasible. In this operation all radars intercepted in the various islands were thoroughly and continuously jammed to prevent them from giving the Japanese one scrap of tactical information.

In October 1944, a carrier task force cruising off Formosa intercepted and jammed the Air Mark VI radar of a Japanese night torpedo plane. This event forced an even broader change in the concept of Pacific radar countermeasures. Strong support was given to the long-standing contention that radar countermeasures in the Pacific could not be handled as a specialized operation in which specific equipment, installations, and personnel were assigned in small numbers to individual ships whose location and objectives would be constantly changing. The problem demanded that radar countermeasures be put on a fleet-wide basis.

In the meantime, far-ranging U. S. submarines had found radar intercept equipment to be of great value against enemy airborne, ship-borne, and shore-based radar. Search receivers had been employed as a defensive weapon to avoid enemy attack, and also as an offensive weapon permitting the tracking down and sinking of enemy vessels. "The ability to detect Japanese radars—shore, ship, and particularly airborne—long before the possibility of being detected by these radars even existed, meant a margin of safety which permitted submerging and other evasive tactics and saved any number of our underwater craft for further rampages among Japanese shipping."[852] For example, the following extracts are quoted from the log of a submarine which was on war patrol in the region of Anguar and Peleliu Islands.

1 August 1944

0400(-9) Commenced approach to east side of Anguar Island. Shortly before 0500 picked up 155 Mc band radar, searching but not training on us.

0500(-9) Now have two 155 Mc radars trained directly on us—one is very strong and close. Our range to Anguar is six miles.

0503(-9) Both radars seem to have us, so dived before they got too much dope. Spent day submerged

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eastward of 8 fathom shoal spot between Anguar and Peleliu Islands.

0900 (-9) Sound picked up light screws bearing 307° (T), not visible from periscope.

0905(-9) Heard distant depth charge. Rigged for silent running. It is possible that a search is being conducted in the area—especially after the radar experience this morning.

4 August 1944

0430(-9) Enemy radar on APR.

0500(-9) More enemy radar.

2125(-9) Enemy radar on 176 Mc. Manned SJ.

2157(-9) SJ contact on port quarter 12,000 yards. Cleared lookouts from bridge. Lat. 7° —04′N, Long. 133° —55′E.

2159(-9) Contact moved rapidly to a position down moon and commenced coming in. Plane sighted at 9,000 yards by OOD, coming in.

2200(-9) Dived with plane closing rapidly. Plane appeared to be a 2-motor bomber. His radar apparently had no trouble in staying on us and he was making a deliberate run from down moon. But for the APR we would have, at best, taken a close one. Especially since I did not turn on the SJ until after APR had contact.

10 August 1944

2300(-9) Dived for radar equipped plane in lat. 6° —45′N, Long. 133° —11′E. Had contact with plane on APR for 15 minutes during which time the signal became progressively stronger. Signal was very loud and steady when we dived. Note that weather was dark, overcast, with frequent rain squalls. Jap planes do not confine their patrols to clear moonlight nights.

11 August 1944

0420(-9) APR signal from land-based radar.

0530(-9) Dived 10 miles east of Peleliu.

2025(-9) Dived when two strong land-based radars came on trained in our sector. We were 8100 yards from beach at this time.

2130(-9) Came to APR depth—radars still on.

2355(-9) Surfaced. No land radar operating.

12 August 1944

1925(-9) Came to APR depth—land radars are on.

2000(-9) Tested again—radars on. Abandoned hope of surfacing close to islands tonight.

2218(-9) Surfaced—seven miles from land. Land radars on, but sweeping.

By the summer and fall of 1944, the pig boats would just as soon have come on patrol without their electric motors as to depart without the radar countermeasures equipment complete and in top-flight operating condition; every boat was so equipped. As experience in the use of this equipment increased, the investigative and defensive uses were supplemented by still another one—the ability to actually locate and hunt down enemy ships simply because they used their radars. . . . This (type of operation) culminated in one particularly outstanding example: The submarine, BATFISH, picked up and homed in on the radar emanations from three Japanese submarines in quick succession. Each submarine was sent to the bottom on (the basis of) this information. From a dollars and cents point of view, the loss of three Japanese submarines alone paid for all our radar countermeasures effort in the submarine force.

By October-November of 1944, radar countermeasures were instituted on a fleet-wide basis. The allowance of radar intercept equipment for each combatant ship of DE class and above (except submarines), including headquarters ships, was established as:

1 RDO receiver,
1 RDJ pulse analyzer,
1 RDP panoramic adapter,
1 DBM direction finder,
1 SPR-2 receiver, and
1 panoramic adapter for SPR-2 (under development).

For submarines, the standard allowance was:

1 SPR-1 receiver,
1 SPA-1 pulse analyzer,
1 SPR-2 receiver,
1 dual-presentation panoramic adapter for use with both receivers (under development), and
1 direction finder (under development).

Cent. Com. Two, Annex B, and later PAC-70 (B), established a consistent policy, doctrine, and plan for the use of this equipment. The basic doctrine stated that

1. All ships shall make maximum use of intercept equipment in order to provide all possible information concerning enemy radars both for tactical purposes and to furnish data to guide the design of suitable countermeasures equipment.

2. *The entire radar spectrum* within the capabilities of the radar intercept equipment available shall be kept under constant surveillance in order that (among other things) new enemy radar frequencies may be discovered at the first opportunity.

3. When contact of the enemy is possible, the OTC shall assign RCM intercept guardships to cover the various bands in which enemy radar activity is expected. The following frequency divisions and designation shall apply:

Guard Able	40–105 mc
Guard Baker	75–300 mc
Guard Charlie	300–1000 mc
Guard Dog	1000–3400 mc

Guard Easy	Current Japanese airborne frequencies in the 75–300 mc band
Guard Fox	Current Japanese airborne frequencies in the 300–1000 mc band
Guard George	Specially designated bands

A single receiver should normally be assigned to guard only one band whenever possible in order to reduce the delay and prevent the confusion which accompanies the shifting of tuning units.

The OTC should direct ships equipped with radar direction finders to take simultaneous cross bearings on any radar signal reported by guard ships in order to locate the enemy radar.

The above doctrine was extended to cover generalized intercept operations required for task forces at sea or at an amphibious objective. For a detailed description of these plans as well as an account of the manner in which they were carried out the reader is referred to subsections entitled "Surface Vessels" which appear under Sections 15.5.3 and 15.5.4. In summary, it will be noted that ship-borne radar intercept equipment performed a variety of necessary and useful functions. At the conclusion of the Okinawa operations, the RCM control officer for Task Force 52 reported that RCM equipment had been used for the following purposes on the USS *Estes,* AGC-12, during that operation:

1. To alert task force to presence of enemy snooper planes before the planes were detected by our radar pickets.
2. To further identify bogey planes which approached from a given direction as enemy, because of the Mark 6 radar signals intercepted on that bearing.
3. To determine whether land-based surface search radars were tracking our disposition by their sudden lack of rotation and increased signal strength, i.e., trained in our direction.
4. To study and analyze the characteristics of various enemy land-based radars while in the vicinity of the objective.
5. To determine the approximate location of these radars.
6. To coordinate this information with that from our photographic intelligence in an attempt to 'pinpoint' the various enemy sets for Naval gunfire purposes.
7. To determine the effectiveness of Naval gunfire and air bombardment on enemy radars by noting whether or not these sets came on again after being under fire.
8. To further identify friendly submarines as such by the interception and identification of their radars.
9. To examine skunk raids for possible enemy surface search and fire control radars.
10. To determine whether or not our radar, IFF, was emitting a pulse of the proper size and shape.

15.5.3 Countermeasures against Enemy Surface Radar

Aircraft

Countermeasures against Japanese ground radar were employed by both land- and carrier-based naval aircraft. However, it was not until the fall of 1944 that Window was used for the first time. Airborne electronic countermeasures were first used in the early part of 1945. It will be remembered that the British first used Window at Hamburg in July 1943. The Germans followed suit on the night of September 6, 1943, at Bizerte. By October 5, 1943, the Japanese had dropped their first Window cut for 200 mc on two simultaneous raids at Dobodura and Kariwina. In this connection it is interesting to note that the benefits to be derived from the Pacific use of radar countermeasures were slow in realization because of the difficulty in obtaining enemy radar intelligence and because of the failure of the enemy to offer a significant radar threat until the later phases of World War II.

According to naval records, the first employment of U. S. countermeasures against Japanese radar occurred in mid-October of 1944, when carrier-based dive bombers attacked Manila prior to the invasion of Leyte. Five units of Navy type, CAFJ 10271 (600), Window, guillotined to 28.2 in. for use against the two 200-mc GL and SLC radar thought to be in the Manila area, were supplied to each plane participating in the attack. All five units were to be dispensed simultaneously as the aircraft reached its push-over point and started the bombing dive. Crew reports indicated that anti-aircraft bursts were particularly heavy in the Window area, but no definite conclusion could be drawn as to the combat value of Window usage at this target. The effect on morale was favorable.

In the first Philippine operation, airborne naval countermeasures played a very small part. Plans had been made to equip and utilize

a small number of TBM's for search and possible electronic jamming if dangerous targets were encountered. Airborne jamming transmitters were not used, however, because several of the TBM's were destroyed before seeing action.

In the Palau operation, during the period August 26 to September 28, 1944, immediately preceding the invasion of Leyte, similar plans were prepared, but no suitable occasion was found for carrying them out.

With this introduction to the use of confusion reflectors and electronic jamming, the naval air arm firmly adopted a policy of utilizing radar countermeasures protection at each heavily defended target which was attacked. The period from October to December of 1944 is characterized by experimentation in each air arm of the various fleets to evolve the most effective countermeasures operating procedure. During the carrier strikes on Shanghai, Hong Kong, and Formosa, carrier aircraft were universally supplied with 200-mc Window or Rope; the larger planes also carried jammers. In some instances, makeshift Window dispensers were installed in fighters. Detailed records of the events in this period are not readily available, but the results of this intensive experimentation are thoroughly evident in the early developments of 1945. With the preparation of a document entitled "Cent. Com. Two, Annex B," a consistent plan, doctrine, and policy was achieved for the *fleet-wide usage* of radar countermeasures.

At the beginning of 1945, then, "Cent. Com. Two, Annex B," offered the following radar countermeasures plans for air operations against enemy ground or surface vessel radar:

1. Jamming transmitters allotted to a carrier for use in carrier aircraft should be used when, in the opinion of the carrier task force commander, the effectiveness of radar-controlled antiaircraft or searchlights warrants the added weight involved in carrying jammers.

2. Carrier aircraft should employ Window in all attacks against heavily defended target areas or large task forces. The first strike over any such area should carry Window cut for frequencies in accordance with the latest information available prior to the operation. Subsequent strikes should carry Window based on the findings of radar countermeasures intercept planes during the first and subsequent strikes, if any change is indicated.

Against fire-control radars, Window should be dispensed immediately before reaching, and while over, the target area and when passing over heavy antiaircraft concentrations en route to the target.

Example. During carrier aircraft strikes, each plane should drop Window cut for the known antiaircraft fire-control frequencies, beginning about 3 min prior to entering a dive or commencing a run.

Against EW radar, Window may be employed, if desired, in an effort to confuse the enemy fighter-direction systems.

3. In the event of a fleet engagement, carrier- or shore-based aircraft were instructed to keep the surface forces covered with a Window-infested area at all times. The Window should be cut for enemy frequencies for which no jammers or shell Window was available in the surface force. Each carrier should be prepared to operate planes in relays to insure adequate and continuous coverage.

Example. Although microwave jammers for use against enemy S-band radars are available in limited quantity, the only generally available defense against these radars is Window dropped from aircraft.

4. For the use of shore- or tender-based naval aircraft, electronic jammers were collected in forward area radar countermeasures pools or at squadron bases. They were to be used when the effectiveness of radar-controlled antiaircraft fire or searchlights so warranted.

5. Shore- or tender-based aircraft were instructed to employ Window cut for fire-control frequencies in all attacks against heavily defended areas or against large task forces when the level of the bomber attack was such that they would be within effective gun range.

Example. During horizontal bombing by large bombers, Window should be dropped at regular intervals by each plane during the last portion of the approach and when directly over the target area.

Against EW radar, Window could be employed if desired in an effort to confuse fighter-direction systems.

6. Specially prepared deception or diversion plans incorporating the combined use of jamming, Window, and deception devices might be undertaken with the proper authorization.

Example. (1) Early-warning Window may be employed to simulate a large number of planes orbiting prior to an attack. In this case, the Window should be sown by the plane or planes while circling and climbing in order to increase the duration of its effect on enemy radars. (2) Planes may sow Window in one area prior to making an attack in another in order to create false alerts and disperse enemy intercepting forces.

Since the above doctrine and policy was to be promulgated on a fleet-wide basis, it was essential that an adequate installation and material plan be instituted. Thus, in order to prepare naval aircraft to carry out offensive countermeasures operations against enemy ground or surface-vessel radar, the following jamming transmitters were authorized and installed.

1. For carrier aircraft usage, equipment was placed aboard CV's and CVL's to provide RCM installations in five TBM's or TBF's of each squadron. The following units were furnished:

5 AN/APT-1,
5 AN/APT-2,
5 AM-14/APT, and
5 AM-18/APT.

2. For each PB4Y2 plane employed in the Pacific Area, the following allowance of electronic jammers was established:

1 AN/APT-1,
1 AN/APQ-2, and
1 AN/APT-5.

3. Three planes of each squadron of other multiengine naval aircraft were authorized to carry the following equipment:

1 AN/APQ-2.

In addition, AN/APT-1, AN/APT-2, and AN/APT-3 jamming transmitters were stored in forward area depots for use by these squadrons when required.

By the early part of 1945, then, a large part of the herculean task of procuring, transporting, and installing the necessary equipments, and the procurement of trained personnel, had been completed. Bold plans had been made for the amphibious assault of Iwo Jima and for an even larger operation in the Nansei Shoto, known as Operation Iceberg. Numerous carrier air strikes would be required against the home islands of Japan itself. Diversionary strikes would be required against Wake, Formosa, and the China coast. The circumstances were favorable, indeed, for the profitable utilization of radar countermeasures by naval aircraft.

One is not surprised, then, when reading the action reports of the USS *Bunker Hill,* CV-17, to find that countermeasures actually played a large role in the Tokyo air strikes which supported the assault of Iwo Jima, as well as in the actual landings themselves. The following excerpts from the log of the *Bunker Hill* were chosen as typical for each of the several carriers participating.

February 16, 1945—Five TBM's, each equipped with AN/APT-1 pre-set to 198-202 Mc, attacked strategic targets and shipping in the Tokyo area. One of the five aircraft was equipped with APR-1 and APA-11. Each VT and VB accompanying the five TBM's was supplied with S- and P-band Window. Electronic jammers were used from land-fall to land's-end. Two hundred Mc and 10-cm Window was dispensed in the target area. No planes lost to enemy action.

Subsequent attack was made by seven VT's, each carrying 47 sleeves of 10 cm Window and 108 sleeves 200 Mc Window.

Subsequent attack by seven more VB's, each carrying 50 sleeves 10 cm Window and 90 sleeves 200 Mc Window.

Crew Comment: All AA bursts downwind.

February 17, 1945—Radar countermeasures applied in fashion similar to previous day.

Crew Comment: AA behind and below.

In this same strike, the commander of Air Group 4 reported that Window was dispensed by F6F's from the Mark 47 miniature bomb rack. AN/APT-1 and AM-18/APT were used for the first time in VT's. Intense, but inaccurate, antiaircraft fire was encountered.

D-Day for the assault of Iwo Jima was February 19, 1945. The shore bombardment groups had been active for several days with only a minimum of carrier air support. On the morning of February 19, however, at the time of the landings, portions of other carrier groups were diverted to the region of Iwo Jima in order to assure unquestioned air superiority and close support bombing for the assault troops. A large

concentration of carrier aircraft remained in the Iwo Jima area until February 22, flying sorties at every hour of the day. Each VB or VT that took off was supplied with 200-mc Window, but no heavy antiaircraft was observed and hence there was no occasion for its use. The single Mark IV Model 3, 200-mc fire-control radar thought to be present on the northern portion of the island had succumbed, together with its antiaircraft guns, to previous naval bombardment.

One important phase of the air operations at Iwo Jima, and later at Okinawa, was the prevention of enemy aircraft reinforcements either to the island under attack or to a near-by enemy island. To obviate this possibility, continuous watch was kept on the neighboring enemy islands, and Japanese air facilities through which replacement aircraft were staged were systematically destroyed. Such an operation involved night patrols for which the protection of RCM was highly desirable. For example, the commander of Night Carrier Air Group 90 based on the USS *Enterprise* reports:

> In strikes on Chichi-Jima, the enemy only used their fire control radar during the first few strikes. Later they were detected turned on for a few seconds at a time. However, as a precautionary measure, jamming and Window were used during all these strikes by Air Group 90 on Chichi and Haha Jima, operating on the theory that if the enemy did turn their equipment on during a run, he did not gain much by it.
>
> Pilots, air crewmen, and administrative personnel, have gained much knowledge of the use of RCM and are highly interested in its future possibilities.

In the interim period between the occupation of Iwo Jima and the assault on Okinawa, widely separated carrier strikes were made at such places as Wake Island and the airfields of Kyushu. In the first instance, the commander of Carrier Air Group 6 reports that RCM was a valuable adjunct to the mid-March strike on Wake. The antiaircraft defenses of this island were considered dangerous to the degree that an antiflak mission was planned prior to the main bombing attack. It was intended that four aircraft, utilizing bombs, machine guns, and RCM, attempt to neutralize the enemy's flak defenses before risking a larger number of aircraft. Accordingly, two TBM's and two F6F's took off from the USS *Hancock* approximately an hour and a half before the main strike was scheduled to bomb the target. These first four planes made their approach toward Wake at an altitude of 200 ft in order to avoid strategic early detection. At a distance of 50 miles from the island, they climbed to 4,000 ft, dropping both 100- and 200-mc Window as they flew on toward the objective. The Window was dropped at this time in order to assist in the definite detection of these aircraft and to alert the enemy to a sector quite foreign to the one in which the main bomber force would attack. At a distance of 10 miles from the island, flying at 2,000 ft and still dropping both kinds of Window, the TBM radar intercept operators logged two enemy fire-control radars at 203 and 207 mc. Jamming was immediately begun with the AN/APT-1's, and within 7 min both radar sets had gone off the air, not to return during the balance of the strike mission. Bombing and strafing of the previously determined flak sites was then accomplished by the four aircraft and the main bomber force came in for its attack 5 min later. No aircraft was lost to enemy action.

At approximately this same time, enemy targets on Kyushu and the Inland Sea were also under attack. Night Carrier Air Group 90 again reported substantial benefit from the use of RCM.

> Air Group 90 has adopted the practice of furnishing all aircraft with Window when operating in enemy areas. The VT's are furnished with type CAFJ-10271 (600) cut to 28.2 in. for use against 200-mc radar. The VF's are furnished with Rope (CHR-2), mainly because it is easier for them to handle.
>
> In every strike the tactics may be somewhat changed so a set plan of procedure cannot always be used. The ideal way would be for special planes to sow Window and use jamming over the target area. When not considered necessary or practical to assign a special plane for this task, Air Group 90 included at least one or two RCM equipped planes in each strike. All planes of the strike were equipped with Window and would dispense while making runs on the target. The planes equipped with jammers would jam while runs were being made.
>
> On the night of 19 March 1945, a VT aircraft in which the RCM officer was the operator, was preparing to make a rocket run on Saeki Air Field, Kyushu, a signal from an FC/SLC radar was intercepted. After being jammed, it was turned off and did not come on again. However, Window was dropped and jamming used while making the run as a protective measure.

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Drawing heavily on their previous experience, naval aircraft made full use of RCM against enemy ground radar during the invasion of Okinawa and islands of the Kerama-Retto. In any invasion, but particularly in those at Iwo Jima and Okinawa, it was necessary for carriers to lie offshore for extended periods of time in order to give continuous support to the beachhead. These valuable ships, in addition to a host of other vessels in the transport area immediately off the beaches, presented vulnerable targets to Japanese land-based aircraft. In order to protect them, as well as the invasion forces, all enemy airfields within range had to be kept under continuous attack. This was done both day and night by land- and carrier-based naval aircraft.

The procedure usually followed was that of sending out three aircraft—normally two fighters and a torpedo plane—to each enemy airfield. These planes would then maintain a continuous patrol with the object of preventing enemy activity on the field below. To avoid accurate SLC and antiaircraft fire, Window, Rope, and electronic jammers were universally employed.

The final blow struck by naval aircraft at Japan's radar and electronic potential came in July 1945. The Third Fleet had planned a series of carrier strikes at important industrial centers on the eastern and southern coasts of Kyushu, Honshu, and Hokkaido. High on the priority list of strategic targets in each industrial center were the radar and electronic manufacturers. Bombing results were excellent. The United States naval air arm, which labored mightily to effect an electronic radar countermeasures program, took the next logical step, a direct countermeasure with high explosives. By this action, an important phase of the antiradar war was ended before the Japanese surrender.

Surface Vessels

Offensive electronic countermeasures against Japanese ground-based radar were undertaken no more than five times by naval vessels in World War II. There is no record of such countermeasures being employed against Japanese ship-borne radar. Quite the opposite is true, however, of defensive ship-borne radar countermeasures, which played a relatively large role in each contact of U. S. vessels with the enemy. The explanation of the slight utilization of ship-borne offensive countermeasures lies in the enemy's failure to offer a significant surface-radar threat to attacking naval forces. The original purpose of Japanese radar development was to strengthen the air defense of the homeland. Until early in 1943, their effort was directed almost entirely toward the development of EW equipment, and it was only at a considerably later date that they succeeded in perfecting searchlight-control or antiaircraft fire-control equipment useful against U. S. aircraft. This latter equipment was not easily adapted for use against surface vessels either from a ground-based or ship-borne installation. Thus, since no serious threat was offered, it is not surprising that U. S. ship-borne offensive countermeasures were used only on a small scale. Because of the continuing possibility that such a threat might unexpectedly develop, extensive precautions were taken.

The first attempt by U. S. naval vessels to counter the effectiveness of Japanese shore-based radar occurred on October 25, 1944, at Marcus Island. In this instance, a small attacking force, in carrying out a diversionary raid, found it convenient to retire from the immediate vicinity of the island at nightfall and reappear for the attack at dawn the following day. On successive nights it was noted that EW radar had tracked the disposition of the surface force each time it retired and again on its reappearance. On the final day of the attack, it was desired to conceal the fact that the group of vessels would not reappear again the following morning. If this retirement could be adequately concealed, the enemy might be deceived into directing reinforcing submarines or aircraft to the immediate vicinity of Marcus Island, thus permitting the attack group to proceed to its base unmolested. Accordingly, on the night of October 25, a quantity of Raywind radar targets were released in a fashion that would most closely simulate nighttime retirement. With luck and a favorable wind, these same targets might indicate an approach some hours later at dawn. No definite conclusion was drawn as to the efficacy of this tactic, but it is

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noted that the attack group proceeded to its base unmolested.

Defensive countermeasures have been of great assistance to U. S. naval operations from the time of the first ship-borne installation of a radar intercept receiver. In August 1943, at such widely separated places as Munda, Marcus, and Tarawa, bombardment and other task forces employed their search receivers during radar silence to determine the exact time when each force was detected by shore-based EW radar. In this way, tactical surprise was carried a few miles closer to the objective under attack with the highly important provision that U. S. forces could usually determine the exact instant of their detection. In the Marianas campaign and later at Palau, extensive ship-borne investigations were undertaken to determine radar-shadow zones along which attacking vessels might approach without fear of detection by shore-based radar. Later on, in the periodic shore bombardment of the Kuril Islands, Iwo Jima, Okinawa, and the home islands themselves, radar intercepts played a similar role, greatly reducing the risk of unexpected enemy action.

With the sweeping decisions made in October-November 1944 to employ radar countermeasures equipment on a fleet-wide basis, past experience of surface vessels encountering shore-based or ship-borne enemy radar was assessed. It was obvious that no serious problems were at that time posed by enemy ground radar. But at the same time, it was generally agreed that precautions should be taken for any eventuality of the future. "Cent. Com. Two, Annex B" and later PAC-70 (B), "Radio and Radar Countermeasures and Deception," achieved a consistent plan, doctrine, and policy for the fleet-wide usage of radar countermeasures against enemy shore-based and ship-borne radar by U. S. surface vessels.

A plan such as the following was offered for task forces at sea which combined the complementary functions of radar and RCM:

1. *Radar and RCM pickets* should be stationed from 20 to 40 miles ahead of the force, either on both bows or in the direction of the most probable enemy attack. These pickets should be equipped with sufficient radar and RCM equipment to conduct a search either by radar, for enemy air or surface targets, or by intercept receivers, for enemy radar signals. Each ship should be prepared to spot-jam an enemy radar when directed.

2. *Screening destroyers* should be disposed in such a manner that they can search for enemy radar signals, barrage- or spot-jam when ordered, or deceive the enemy by means of Gulls, Kites, or shell Window.

3. Larger ships were required to perform a variety of functions, including supplementary RCM search, jamming, or deception, in addition to radar tracking or fighter-direction control. In particularly large dispositions, radar jamming by ships in the screen was to be supplemented with jamming by interior units in order to create maximum confusion on the enemy's radar presentation and lend additional protection to the interior units if the enemy should penetrate the screen.

All ships having RCM equipment were assigned intercept and jamming duties in one or more of the following RCM guard bands:

Able	40– 105 mc
Baker	75– 300 mc
Charlie	300–1,000 mc
Dog	1,000–3,400 mc.

4. The overall coordination and control for the use of radar and RCM equipment in a task force at sea fell to the Officer in Tactical Command [OTC], who might delegate actual control to a force RCM control officer aboard a vessel with superior RCM facilities. In combat, this officer might follow one or more of the standard tactics (or, as sometimes happened, devise and approve a new one on the spot). Standard tactics included

1. Screening of the entire force by shell Window or aircraft-dispensed Window in the event that enemy radars were encountered for which no jammers were available.

2. Deception by Gulls or other reflectors at night or under conditions of restricted visibility.

3. Screening of the entire force, in the event of a fleet engagement, by the use of all available jammers against all enemy radars encountered,

with particular emphasis on enemy fire-control radars.

In order to permit the carrying out of this generalized plan on a fleet-wide basis, an installation and material program of sweeping proportions was instituted by January 31, 1945. The following offensive RCM equipment was authorized:

1. For all headquarters ships, cruisers, aircraft carriers, battleships, and destroyers of the 445 and 692 class, the following radar jammers:

1 TDY transmitter (60 to 1,200 mc)
1 S-band jammer (under development)

2. Suitable supplies of Window-loaded projectiles covering known enemy fire-control frequencies for all combatant vessels of DD class and above.

This program, because of its comprehensive nature, was familiarly known as the "Ultimate Installation Program"; its completion was to cover a period of several months. But the insurance value of RCM equipment could ill afford a delay of this length. Even before the promulgation of this ultimate program, interim installations had been proceeding at a rapid rate. Jamming equipment originally designed for aircraft usage had been cleverly adapted to ship-borne installation. For example, two or more of the equipments listed below,

AN/SPT-1,
AN/SPT-4 or AN/APQ-2,
AM-14/APT,
AM-18/APT,

had, by the late fall of 1944, been installed aboard the following:

7 battleships
3 cruisers
12 carriers
44 destroyers
6 headquarters ships (AGC)
3 YMS
3 LCI (G)
45 LCI (L)
2 DM.

Thus, in the early part of 1945, naval forces were in an excellent position to reap the benefits of the past countermeasures effort. Generalized RCM tactics and doctrine had kept pace with an adequate installation and training program to a degree that gave U. S. forces an overwhelming advantage in that phase of electronic warfare involving countermeasures against enemy shore-based or ship-borne radar. Such an opportunity presented itself with the plans for the invasion of Iwo Jima.

Previous reconnaissance of Iwo Jima, both by intercept receivers and aerial photography, had revealed the definite existence of as many as four radars. With one exception, a Mark IV Model 3, all equipments were believed to be of the EW type operating either in the region of 100 or in that of 150 mc. No intelligence specific to Iwo Jima indicated the presence of gun-control radar suitable for directing shore batteries onto naval targets. Generalized intelligence on the state of Japanese radar development substantiated this conclusion, but left some margin for doubt. With this information, an operational order was written into the invasion plans which directed the establishment of a 24-hr intercept guard from 40 to 3,400 mc according to the policy of "Cent. Com. Two, Annex B." Offensive countermeasures were to be employed only at the discretion of the OTC, since the need for employment against shore-based radar, judged in the light of previous intelligence, was not thought to be great. Other portions of the operational order were concerned at length with the more dangerous probability of attack by enemy ASV-equipped bombers. (See subsection "Surface Vessels" of Section 15.5.4.)

As the operation commenced on February 16, the amphibious assault force, Task Force 52, engaged itself in an intensive shore bombardment. During this time, a 24-hr intercept watch was maintained and a complete log of the island's radar operations secured. From this it was found, generally, that the EW equipments were operated only at night after bombardment had ceased, most likely attempting to monitor the disposition of our forces in the hours of darkness. The period of operation of any one radar was irregularly intermittent. Numerous attempts were noted to change the characteristics of these radars, probably in an effort to

confuse our intercept activity. The single fire-control radar on the island was observed to operate only at night in the presence of Allied aircraft.

On the morning of February 18, a signal was intercepted with characteristics similar to the Japanese Air Mark VI (ASV) and some ships began jamming on a frequency of 152 mc. Further checking aboard the USS *Estes,* AGC-12, indicated that this was a stationary ground radar located on the northeast portion of the island, probably of the Mark I Model 3 type. Jamming was immediately secured since no purpose was being served, and since, in the confusion, undesirable interference to U. S. radars such as the SC and SK was created.

Before beginning the short bombardment phase of the operation, the EW radars of the island had been evaluated as a necessary evil of no great importance to the enemy's immediate tactical position. With this evaluation, no particular emphasis was placed on their destruction by naval gunfire. In fact, it was hoped that they might be captured intact and serve as an additional source of intelligence. In the light of this, it is particularly interesting to note that by noon of February 18 the Japanese had become aware that their radar sets were not being used as bombardment targets. Quickly taking advantage of this fact, numerous stores and some lighter weapons were concentrated at these locations. This change in disposition of enemy defenses was easily detected from aerial photographs and a good portion of the afternoon of February 18 was allotted to the systematic destruction of each of the island's radars and its surrounding area. By the night of February 18, the last of the enemy's ground-based radar had been destroyed. The 24-hr intercept guard was necessarily continued, however, to assist in defense against airborne enemy radar.

Following the assault of Iwo Jima, a number of diversionary strikes were undertaken to prepare the way for the later invasion of Okinawa. The record indicates that these strikes, with one exception, involved no use of offensive countermeasures against ship- or shore-based radar. The single exception occurred at Zamboanga on the night of March 9, 1945, when the commander of Task Group 74.3 ordered the USS *Boise,* CL-47, to jam a signal which had first been intercepted on 600 mc and slightly later on 606 mc. An identification of this signal was never satisfactorily made, nor were the results of the jamming ever definitely evaluated. This operation is notable, however, because it represents an unpredicted, unexpected event in which the precautionary program for offensive ship-borne countermeasures was called into use.

The final incident in the story of ship-borne countermeasures against enemy ground radar came with the planning and execution of the invasion of Okinawa. An elaborate reconnaissance of all features of the enemy defense in the Okinawa-Gunto had been carried out before definite plans were consummated for Operation Iceberg. This reconnaissance had included radar intercepts by aircraft, surface vessels, and submarines, as well as small-space and large-scale photographic reconnaissances permitting detailed pin points of several radar sites. Assessment of this information revealed that the enemy's radar defense was probably limited to EW equipment. A total of 10 to 12 such sets was eventually found, including the 7 listed below:

2 Mark I Model 3
2 Mark I Model 1
2 Mark B
1 Mark CHI

In planning the operation, past experience, including Iwo Jima, strengthened the conclusion that ship-borne jamming of EW ground radars would serve no useful purpose. Accordingly, the operational order specified the conventional 24-hr intercept guards, with the addition of definite jamming plans for protection against enemy airborne radar. (See subsection entitled "Surface Vessels" of Section 15.5.4.)

The operation itself commenced with the simultaneous invasion of the Kerama-Retto and the shore bombardment of Okinawa on March 26. During this period, a comprehensive log was kept of all enemy radar operation and the task was begun of keying known radar locations with radar intercepts. As at Iwo Jima, the operating periods of enemy radar were irregularly intermittent, with some preference of nighttime

operation. Frequency, pulse widths, pulse-repetition rates, and even the physical locations of several Okinawa radars were changed without notice. During shore bombardment periods, no more than three radars were known to operate at any one time. Moreover, it was found that the enemy had a coordinated warning net to the extent that operation of individual radar sets could be shifted up and down the southwest coast of Okinawa in accordance with the center of U.S. naval activity. With the extended opportunity to observe Japanese ground radar at close quarters, naval RCM operators drew several interesting conclusions.

1. The changing characteristics, location, and intermittent operation of enemy radars were thought to stem from the Japanese awareness of RCM facilities aboard U.S. naval vessels. It was believed that the Japanese hoped to conceal by these means the true number of radars in operation within a given area and to hinder accurate location of any particular set.

2. The Mark B radar, as exemplified by a particular set in the vicinity of Yonabaru, appeared to be capable of tracking large surface vessels at ranges of 17 to 20 miles.

3. The Mark I Model 3 radars behaved in a manner which led one to suspect their use as a source of beamed energy which, if coordinated in frequency with the Air Mark VI (ASV) or similar type of gear, might be used to guide enemy aircraft or suicide boats to U.S. surface dispositions.

The latter conclusion, if true, represented a situation sufficiently dangerous to the vulnerable collection of ships immediately offshore that it was made the subject of an extended experiment involving electronic jamming of shore-based radar from surface vessels. The USS *Robert H. Smith,* DM-23, and the USS *Wadsworth,* DD-516, took turns jamming a particularly suspicious 93-mc mobile search radar from May 23 to June 6. Throughout this period, the behavior of this radar was closely scrutinized at the time of an enemy night air attack, and, with time, its correlation either in direction of scan with the experienced air attacks or in coincidence in frequency with enemy airborne radar was finally judged insignificant. Jamming was discontinued at this time with no definite conclusion as to the degree of coordination between enemy air and ground radar for the night location of surface targets.

In essence, the main contribution of RCM to the Okinawa invasion involved offensive countermeasures to airborne enemy radar which

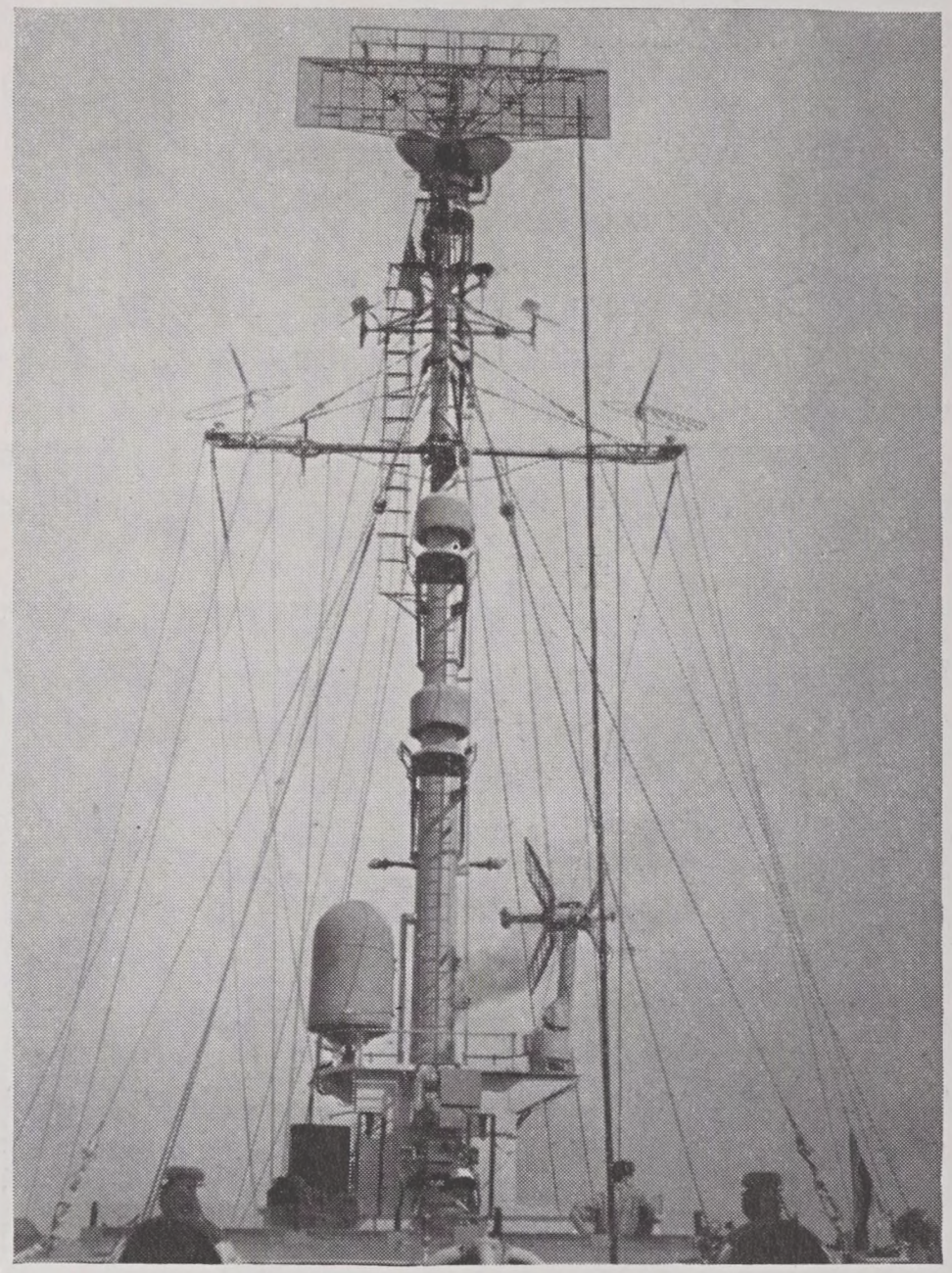


FIGURE 4. RCM and radar antenna installation of the aftermast of a destroyer. Pictured here, from the base upwards, are the following RCM antennas: 1 TDY-1A, S-band, transmitting antenna; 1 TDY, low-frequency, rotating-head antenna (transmitting and receiving); 1 AS-45A/APR-6, high-frequency, wave-guide, receiving antenna; 1 DBM-1, high-frequency, rotating-head, receiving antenna; 1 DBM-1, low-frequency, rotating-head, receiving antenna; 2 CAGW-66132, low-frequency, stub-type, receiving antennas with ground plane; 2 CAGW-66131, cone-type, higher-frequency, receiving antennas with ground plane; 1 AS-44/APR-5, cone-type, S-band, receiving antenna.

are described in Section 15.5.4. As an adjunct to this function, the conventional intercept guards were maintained in order to discover, if possible, the operating procedures which governed the use of enemy EW radar. Apart from the examples of the preceding paragraph, this inter-

cept operation further assisted by eliminating a particularly annoying Mark CHI radar. It was discovered that this radar in the vicinity of Chinen Saki was being used deliberately to jam the voice communication circuit of the TBS equipment operating at 72.2 mc. Direction-finding fixes obtained from the TDY rotating antenna were sufficient to permit low-level reconnaissance photographs to pin-point the enemy set, and naval gunfire put it out of action.

15.5.4 Countermeasures against Enemy Airborne Radar

Countermeasures against Japanese airborne radar were employed by U.S. aircraft, surface

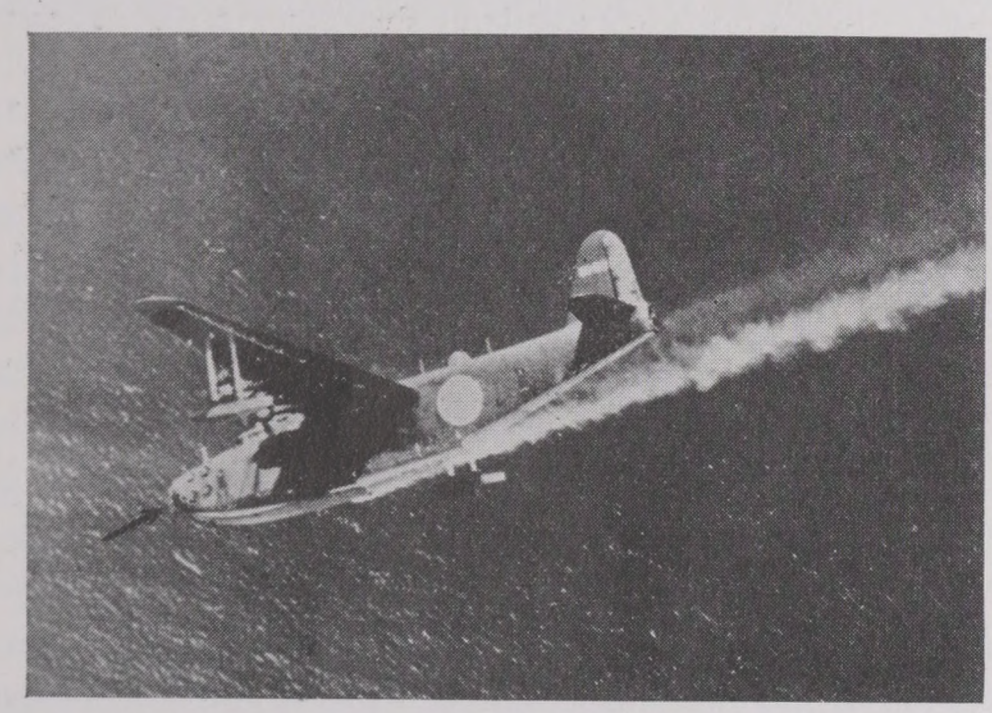


FIGURE 5. Japanese patrol bomber probably equipped with ASV type radar.

vessels, and submarines. From the record of naval operations, it appears that the Japanese airborne radar, in actual combat, proved to be the most dangerous of all Japanese radar in World War II.

The particular equipment, known as the Air Mark VI, which threatened naval forces was not far advanced by U.S. standards. In fact, it was similar in many respects to the first ASV equipment used on U.S. patrol aircraft at the outbreak of hostilities, which was finally judged obsolete by the middle of 1942. In common with all types of ASV radar, the Japanese Air Mark VI permitted reconnaissance aircraft to monitor the movements of fleet units in a vastly increased search sector. A target, once found, could be kept under surveillance at distances great enough to hinder interception or to prevent the ranging of surface antiaircraft guns. (Airborne radar, in comparison with surface radar, has a decided range advantage because (1) it operates on an "elevated platform" and (2) the normal ASV target, a ship, has a much larger echoing area than an aircraft.) In particular, the task of naval combat air patrols in destroying Japanese Mark VI-equipped spotter aircraft was rendered much more difficult since more and more patrol aircraft were required to protect adequately any given disposition of vessels. Moreover, Japanese night torpedo planes often used ASV-type radar in the initial phases of their attack. Later on, Kamikaze attacks were sometimes directed from Mark VI-equipped aircraft. For these reasons, then, enemy airborne radar constituted a serious threat to U. S. naval operations and considerable countermeasures effort was successfully expended to deny the enemy full use of this equipment.

Fortunately, the first operational use of this enemy equipment did not occur until early October of 1944. As in the case of nearly every Japanese radar, U.S. forces had ample advance information that such equipment might soon become operational. It will be remembered that in April 1944 the receiver portion of an early Air Mark VI radar was captured at Hollandia. In the invasion of Saipan, a complete equipment was found intact together with its spare parts. From a Kate found in the same hanger with the Saipan equipment, the antenna and installation practices were also known. Early models of this set had operating characteristics of

Frequency	150 mc
Pulse-repetition frequency	250 (later models had a prf of 1,000)
Pulse length	10 μsec
Peak power output	5 kw.

Later on, by the end of November 1944, a considerably improved model known as the Mark VI Model 4 was captured on Mindoro. Because of the numerous operational encounters involving this equipment, the importance of determining its exact capabilities was clearly under-

stood and extensive field tests were performed in the Hawaiian area by ComAirPac to obtain an accurate evaluation both of the set's operating capabilities and of its susceptibility to jamming.

It is believed that the Air Mark VI equipment was developed and used principally by the Japanese Navy. A similar equipment, known as the Taki Model I, operating on 200 mc, was later developed for use in Japanese Army aircraft.

AIRCRAFT

Since the ability of Japanese airborne radar to detect and track aircraft targets was slight (that is to say, its performance as an AI-type equipment was poor), it would not be expected that U.S. aircraft need employ offensive countermeasures against this particular set on any great scale. In point of fact, this proved to be true, and there is no record of any naval operation in which an airborne jamming transmitter was used against enemy ASV-type equipment. On the other hand, intercept equipment in naval aircraft provided some spectacular examples of a newly developed AI tactic. In general, the enemy plane, when using its radar in the search for surface targets, emitted a signal that could be picked up on a radar receiver at distances greater than 60 miles. With the use of airborne DF systems such as the AN/APA-24, or better still, the AN/APA-17, it was sometimes possible for an interception to be effected. Such an interception procedure was based on the preliminary direction of the interceptor aircraft in accordance with DF cuts on a definitely identified Air Mark VI signal. Following an interception course, the range was closed until the victim was within radar range of the interceptor plane. From this point on, the technique was in all ways similar to conventional radar interception without ground control.

The first, and certainly the most spectacular, example of this type of tactic occurred in the fall of 1944 near Formosa. The incident is described here in the words of the commanding officer of VPB 116, a PB4Y search squadron then based on the island of Tinian.

> One interesting use of RCM equipment came up at that time. The Emily is using radar and apparently it is using radar similar to our original Easy gear, which has a homing position forward and search antennas on either beam, alternating between the two. One of our planes on a sector search out toward Formosa had been instructed that there was a surfaced crippled submarine coming back escorted by three others. He was about 800 miles from Saipan at the time. The searcher's orders were incidentally to give any air cover he could. When our plane was about abeam of this submarine, and had the submarine on his radar screen, he picked up on his RCM equipment an indication of a transmission, which appeared to the technician running the scope as Japanese airborne radar. It had the frequency that the Japanese submarines have used, but the PRF count was a good bit different. He suspected it to be airborne, as he got a peculiar build, then black out, then a weaker signal, and then black out, which indicated that a switch from search to homing antennas took place. He has previously been acquainted with this type from the old PBY equipment. He drew the pilot's attention to it, made a very rough, I'd say guess, but he said estimate, that it was ahead about 90 miles. How he got the distance I don't know, except by what he claimed, signal strength. He homed the pilot toward it. After about 15 to 20 minutes he told the pilot that they were very close; the pilot dropped his search gear and picked up an enemy aircraft blip on the search gear within a six mile circle, obviously below him as he was on top of a .6 cumulus. All the pilot did was get lined up, push the nose over, and man all guns. When he came out of the clouds he was right over an Emily, which at that time was about 20 miles from our crippled sub. The Emily used the old tactics of jettisoning his depth charges as the old PBYs used to do. Fortunately, the pilot was an ex-PBY man and jumped over the explosion and kept coming in. That encounter, I thought, was a rather unusual use of RCM at the time, but it is going to be used that way consistently in the future as Jap use of radar on their aircraft becomes more common. For that reason, the RCM should be standard on our planes now, and I think we are getting them in all our PB4Y-2s. It is going to be an excellent addition for search. You can pick Japs up from 90 to 100 miles away with it.

The possibility that RCM intercept receivers and DF or homing antennas offered a new interception technique was welcome news that spread rapidly through the fleet. By the end of 1944, numerous elements of the naval air arm had experimented with this possibility, often with makeshift equipment designed and installed at sea or in the forward areas. For example, the commanding officer of Night Carrier Air Group 41, based on the USS *Independence*, reports:

> Our own RCM equipment was just getting out in quantity when I left. We had three planes with it in-

stalled and it apparently worked very well. We mounted an experimental radar homing antenna in a TBM in connection with the RCM receiver, and on its first flight it picked up a Jap plane off the coast of China, about 50 miles away, and got a bearing to within 5 degrees. Coming back in towards our own Fleet it picked up the SK at 185 miles at 12,000 feet. There are very great possibilities in the use of gadgets of that kind where our own planes home on enemy transmissions. The enemy apparently thinks we have a lot more equipment of that sort than we do, however, because their snoopers are coming in to within 15 to 20 miles of the formation, staying right on the water, leaving their radar off, and then popping up every 15 minutes or so, turning their radar on for about 45 seconds, taking a real good look and then going back down. The problem of night interception is getting more and more difficult as the enemy learns more and more about it; so we have to hop fast to keep up with them. . . .

The radar countermeasure equipment we got seems to be very satisfactory. It was easy to install, easy to use. . . . I won't go into that any more except to reiterate what I mentioned before about the use of that countermeasure receiver with homing antennas. That is going to be very important in the future.

By March 1945 this tactic had been accepted and was actually included in the operational orders of Night Carrier Air Group 90 based on the USS *Enterprise*. From the following excerpt from a report by Air Group 90's RCM officer, it will be obvious that, though the tactic was accepted and utilized, experimentation continued.

The last two operation plans have carried a plan whereby an RCM plane was to attempt to intercept the radar signal from an enemy aircraft, take a bearing on it, and proceed in that direction until it could be picked up by radar. Then an attempt was to be made to vector a fighter after the enemy plane.

Air Group 90 tried this once north of Iwo Jima. Two planes were sent out when an attack was expected to try and detect the approach of enemy planes and give a warning before they could be picked up on the ship's radar. No airborne signals were intercepted and no attack developed.

The first indication had by this group that something might be accomplished along this line came from a report by one of the radar officers on a flight to the Inland Sea. This officer intercepted a signal which he believed to be airborne. Its bearing was 5 degrees port. He informed the radar operator to be on the lookout for an aircraft target on his scope and it was only a matter of seconds before the radar operator did pick up an aircraft about 5 degrees to port, distance 6 miles. Regrettably, no follow-up was made on this contact as a different objective was in view.

It is suggested that tests be made on these lines where facilities are to be had, as it might facilitate the development of the techniques to be employed. Also, along this same line, it is suggested that operators be taught how to distinguish an airborne signal from that of a land based air search radar. None of our RCM men had received anything along that line and there is not much chance in an advanced area to show them the difference until they actually see one. Then, the operator is not always sure of himself.

Another new possibility suggested itself recently. Six of RCM VT aircraft returned from a mission and found the force, including the *Enterprise*, under attack. While orbiting and waiting for the attack to be over, at least three of the RCM operators intercepted signals which they believed to be airborne. No jamming was done because it was feared that confusion to some of our own ships might result. The fact rates consideration that in a similar situation and upon direction from the ship, RCM planes might jam on the enemy frequency and aid the outcome considerably. It has been noted in other reports of instances where enemy aircraft turned away when their radar was jammed by surface units.

Surface Vessels

Of all Japanese radar, the enemy airborne equipment, it will be recalled, offered the greatest threat to U. S. naval operations. Ship-borne countermeasures were consequently employed on a large scale to deny the enemy full value from his ASV-type equipment—the Air Mark VI, the Taki Model I, or similar sets. As early as April 1944, U. S. forces were alert to the fact that enemy ASV equipment might soon become operational. Fortunately, interim installation and training programs were proceeding in the fleet on a precautionary or insurance basis (see subsection entitled "Surface Vessels" of Section 15.5.3). Jamming transmitters such as the AN/SPT-1, AN/SPT-4, AN/APQ-2, AM-14/APT, and AM-18/APT, originally designed for aircraft usage, had been cleverly adapted to ship-borne installation. By the middle of September 1944, over 50 such interim installations had been completed.

In the first week of 1944

a carrier task force cruising off Formosa was attacked by Japanese night torpedo planes equipped with ASV-type radar. This happened "only once"; when the Japanese returned the next night it was quite a different story. Rapid modifications had been made in existing jammers to cover the Japanese airborne radar frequencies. As soon as the signals were picked up the next night, jamming was commenced. The effect was

startling. The hitherto intrepid Japanese pilots literally blinked in amazement. This was something new, something not looked for. Off went the radars and the planes commenced orbiting aimlessly at a safe distance from the task force. Those who were not shot down subsequently by our night fighters, took home a very perplexing tale. . . .

The reports of this fleet action, when digested and evaluated, gave unequivocal support to the long-standing contention that radar countermeasures in the Pacific could not be handled as a specialized operation in which specific equipment, installations, and personnel were assigned in small numbers to individual ships whose location and objectives would be constantly changing. The problem demanded that radar countermeasures be put on a fleet-wide basis.

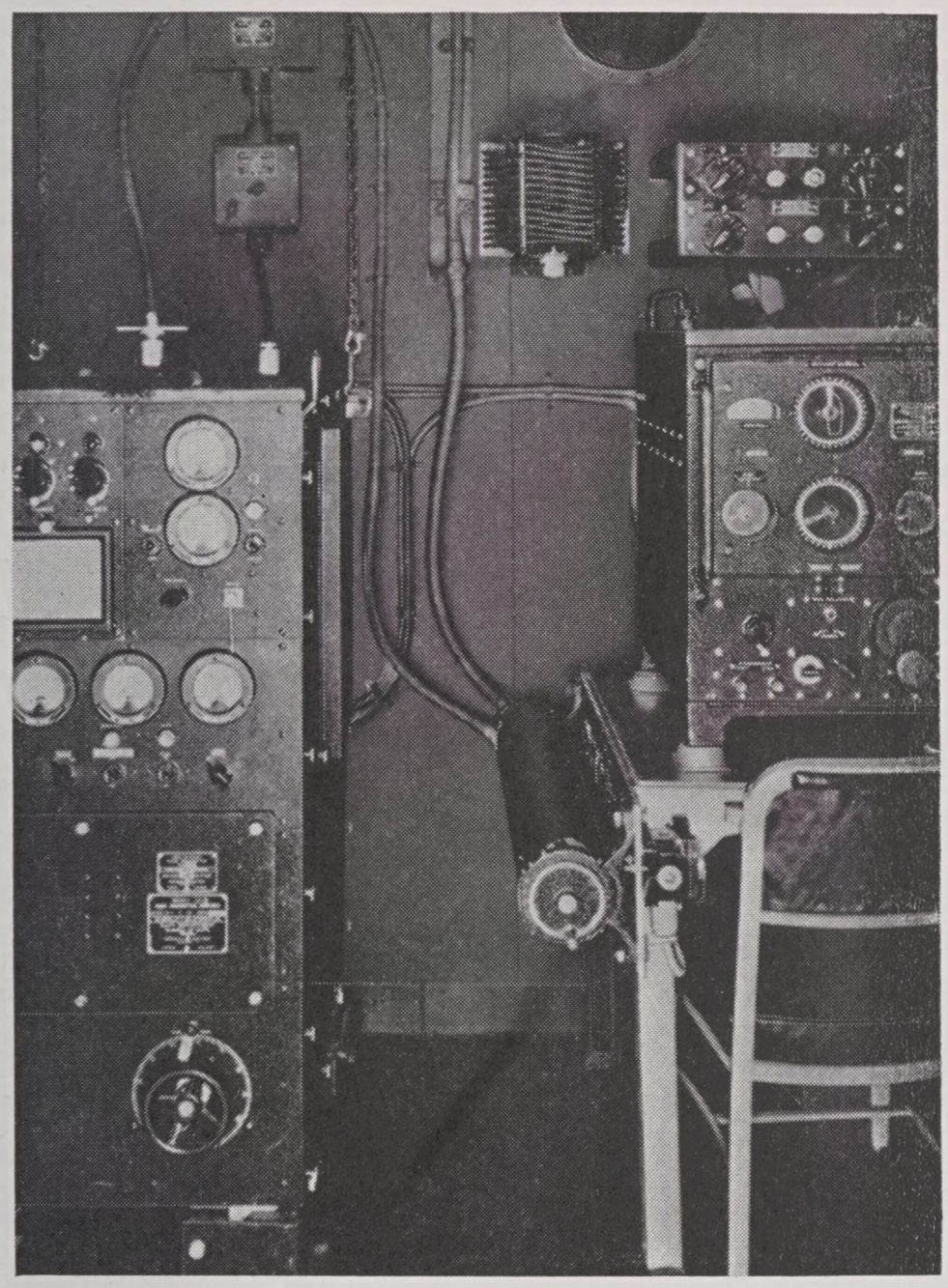


FIGURE 6. Typical ship-borne installation of a TDY-1A, S-band, jamming transmitter and antenna-control system.

As a result, the Electronics Division in the Office of the Chief of Naval Operations, plus the Electronic Sections of the Bureau of Aeronautics and the Bureau of Ships, authorized and implemented an ultimate RCM program. This was the inception of a program which, sometime later, was outlined for the tactical aspect in Cent. Com. Two, Annex B and PAC-70(B), and for the material aspect in CM and D Bulletin-Issue Number 14.

Before this program could be put into operation, however, much experience was to be gained from the numerous encounters with the Japanese Air Mark VI which followed closely on the heels of its first operational use. The small-scale interim program was to pay dividends many times in excess of its original investment.

At the time of the first Philippine landings, portions of the Third and Seventh Fleets were disposed off Leyte Gulf and in the Surigao Strait. October 19, 1944, signals the first instance in which several radar-equipped Japanese aircraft operated simultaneously against large portions of the U. S. Fleet. During the early morning hours, Japanese spotter aircraft watched fleet movements with the aid of radar. The USS *Leutze,* DD-481, intercepted and jammed an Air Mark VI signal, and the Japanese reaction was similar to the first instance off Formosa. That night, as a destroyer task group approached the shores of Leyte Gulf, Japanese Bettys and Vals, serving as night torpedo planes, approached for a radar-assisted attack. All available AN/SPT-4's in the force were tuned to the frequency range 152 to 157 mc, and jamming was commenced. In the face of this barrage no torpedo attack was made. The enemy aircraft approached no closer than 10 miles and one by one turned off their radars, orbited, and finally returned to base. In the succeeding days, similar attacks, either at night or under conditions of low visibility, were made with the aid of the Air Mark VI. The Japanese, at first thoroughly confused by the surprise of jamming, began to experiment with antijamming [AJ] techniques. On October 21 the USS *Robinson,* while jamming an Air Mark VI, noted that the enemy signal when jammed would turn off and reappear slightly later on a frequency some 2½ mc higher. The RCM operator kept pace with the shifting of the enemy radar frequency from 152 to 160 mc in four successive steps. Tiring of this fruitless battle of wits,

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the Japanese attacker went home discouraged. Other attacks were noted in which the enemy operator, in the face of jamming, would turn off his equipment, wait for the jamming to cease, and then turn it on quickly for a free look. Even as the enemy in this particular locality was becoming educated to AJ measures, U. S. operators were simultaneously becoming more skilled in their offensive RCM operations.

By the evening of October 24, when it was known that a Japanese task force was on its way to attack, all U. S. vessels were alerted and on the watch. Enemy spotter aircraft were expected momentarily. The USS *Hutchins* and the USS *South Dakota* both intercepted enemy ASV signals at this time and successfully jammed them, thus giving U. S. forces added time to maneuver before finally engaging the enemy force. The ensuing battle of Surigao Strait is well known. Japanese radar played a very small part in this and the later phases of the first Philippine operation. As the engagement started, ship-borne enemy radars were intercepted, but one by one were heard to leave the air after an attack by U. S. aircraft. Japanese aircraft, disillusioned by their previous experience with U. S. jamming, placed less and less reliance on their ASV radar as their tactics became more and more bold. In the period from October 19 to October 30, enemy aircraft ran the full gamut of attack philosophy: All the way from that of staying away from the U. S. forces during bombardment periods to that of full Kamikaze action. When the enemy became committed to the latter tactics, his use of airborne radar declined to the vanishing point.

As the reports of this and other fleet actions returned to the Commander-in-Chief, U. S. Pacific Fleet, their assessment substantiated the sweeping decision made in October-November 1944 to employ radar countermeasures equipment on a fleet-wide basis. In large measure, these reports assisted in the preparation of a consistent plan, doctrine, and policy for the tactical employment of the large quantity of countermeasures equipment then being installed. One is not surprised, for example, to learn from Cent. Com. Two, Annex B, that

> as of December 1944, the principal enemy radar threat is the use of 150-160 megacycles for airborne radars in snoopers and torpedo planes. Barrage jamming in this band can be accomplished by modified SPT-4 (rug) jammers on ships without RCM personnel. Spot jamming ships would also be required whenever barrage jamming is employed; these spot jammers should be on ships with RCM personnel, intercept receivers and jammers capable of jamming enemy signals between 100-160 megacycles.
>
> Recommended procedure is for RCM technical personnel to stagger-tune the barrage jammers to cover the 150-160 megacycle band. The frequency spread between jammers should not exceed 2.5 megacycles whenever possible.

Jamming tactics against enemy airborne radar were envisaged in the instance of task forces at sea and of amphibious land operations. Specific plans applicable to the former instance are set forth in the subsection entitled "Surface Vessels" under Section 15.5.3. For the latter, plans similar to those below were conceived. In both cases the problem of denying the enemy full use of his ASV-type radar involved

1. The earliest possible interception and identification.
2. The rapid inception of appropriately tuned spot- or barrage-jamming signals.

Small vessels, usually of the destroyer class had been singled out to serve as pickets for early-warning radar purposes. The maneuvers of a radar picket were quite consistent with the need for early interception and identification of enemy radar and the complementary functions of radar and RCM equipment were quickly realized. The result was a combined radar and RCM picket. The rapid creation of a jamming signal was a problem of adequate communications and trained operators. Fleet plans for radar and RCM pickets included the following.

1. One of the most important units in the RCM technical organization is the RCM picket ship whose function is to provide the OTC's RCM control with early information on enemy radar activity.
2. An RCM picket ship should have RCM intercept equipment and adequate communications facilities. Trained personnel are required, and radar jammers are an additional desirable feature. Suitable ships should be fitted to serve as combined Radar and RCM Pickets whenever practicable.
3. Normally RCM pickets should be stationed far enough away from OTC RCM control to allow time after receipt of intercept information to initiate jamming action to confuse or frustrate a threatened attack.
4. Two types of Radar and RCM Pickets were dis-

tinguished: *Distant pickets* should maintain continuous intercept guards for enemy airborne radar and be prepared to spot-jam when directed. *Other pickets* should maintain intercept guards for all frequencies from 40-3400 megacycles without special regard to the 150-160 mc enemy radar band.

For amphibious operations the following technique in the use of radar and RCM pickets in the region of an amphibious objective was recommended.

1. One or more destroyers should be stationed as a distant picket about 50 miles from the objective or transport area in the direction of possible enemy air attack.
2. Fighter Director destroyers, as available, should be stationed around the objective as Radar and RCM Pickets roughly at a 15 mile radius from the transport area. Stations assigned should be selected with due regard for the topographical features of the objective as well as direction of probable enemy air attack.
3. Ships in the transport area other than the flag ship of the Attack Force Commander may be used to supplement the Radar and RCM Pickets.
4. The Attack Force flagship (AGC) should maintain a continuous overall RCM guard and should carry the Force's RCM Control Officer as well as the Force's Fighter Director.
5. Small craft and landing craft fitted as spot jamming and barrage jamming ships, should be placed about two miles from those ships to be screened and at about two-mile intervals around them. If an insufficient number of jamming ships is available to surround the area to be screened, a group of several barrage jammers and at least one spot jammer should be placed two or three miles toward the direction of the enemy's most probable approach.

With the invasion of Luzon, the numerous lessons learned in the U. S. Fleet were put to excellent use in denying the enemy full value from ASV-type equipment. At Lingayen Gulf, during January 1945, Admiral Kincaid, Commander Luzon Attack Forces, was stationed aboard the USS *Wasatch,* AGC-9. The force RCM control officer was also aboard this vessel and this close contact with the OTC resulted in the first blanket plans for the jamming of Air Mark VI signals, in the frequency range 150 to 160 mc. The jamming of enemy airborne radar from vessels of this force became a common occurrence. Within the attack force itself, more detailed plans were made for the carrying out of the OTC's blanket authorization. For example, the Commander of the Second Carrier Task Force authorized jamming of all signals in the frequency range 150 to 160 mc with Air Mark VI characteristics, providing the enemy aircraft was within 45 miles of U. S. vessels. Such authorization was of great assistance, as is seen in a report from the USS *Bismarck Sea,* CVE-92. This vessel was constantly shadowed by enemy spotter aircraft at night. In every instance in which the spotter aircraft were radar-equipped, electronic jammers were immediately used. In no case did the enemy aircraft approach closer than 10 miles.

With the preparation of plans for the invasion of Iwo Jima, the tactical doctrine for the use of RCM against enemy airborne radar was advanced. Installation and training programs had progressed to the point where a substantial RCM effort could, if necessary, be concentrated at Iwo Jima to assist in protecting the large number of ships which would be required. Accordingly, operational orders were prepared in

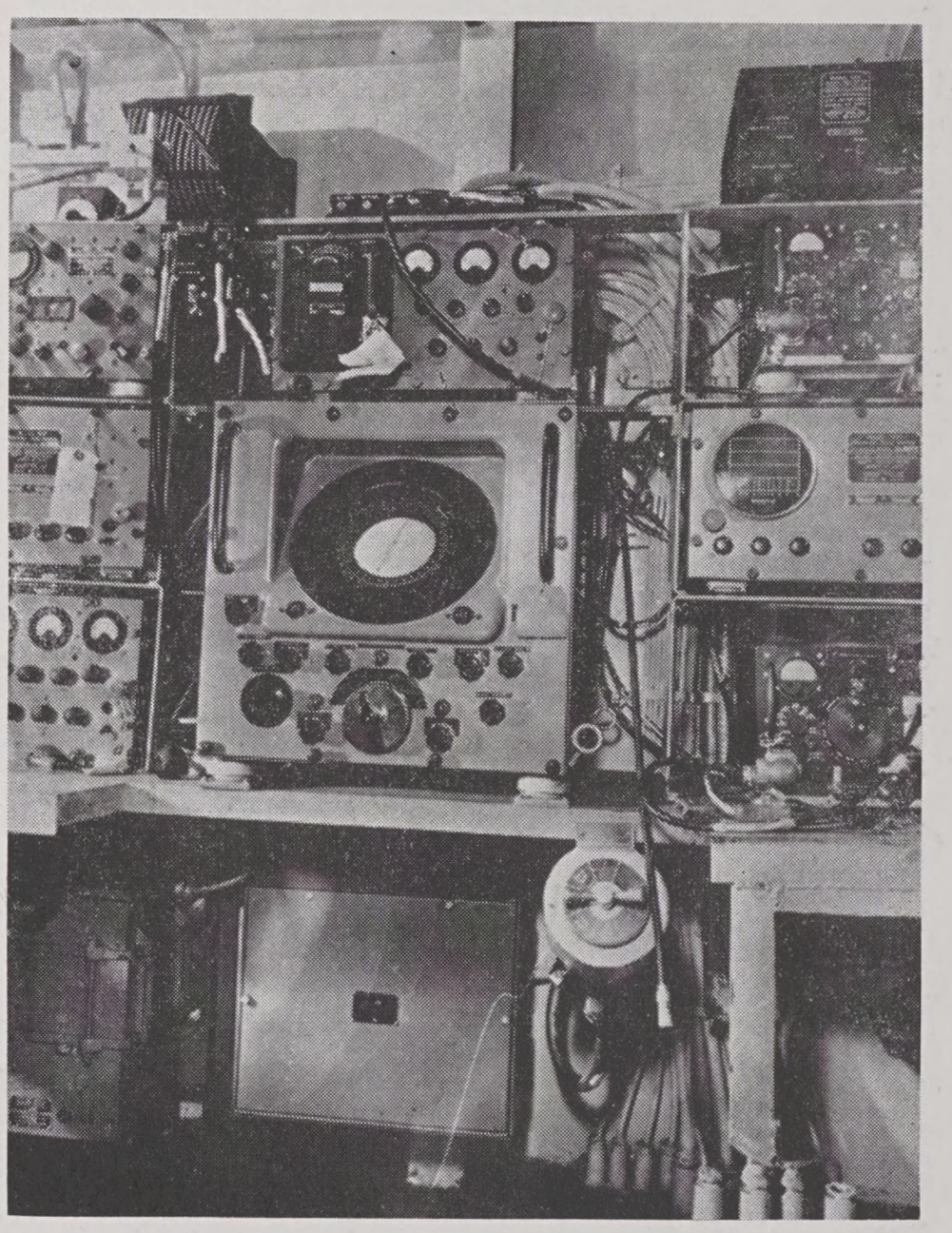


FIGURE 7. Typical ship-borne installation of DBM-1, rotating-head, direction-finding antenna and associated receivers.

which intercept guards were established from 40 to 3,400 mc, in accordance with "Cent. Com. Two, Annex B." Specific jamming orders were not written but left to the discretion of the OTC. Fully aware of the threat from enemy airborne radar attacks, however, several LCIG-RCM as well as newly complete radar and RCM picket vessels were assigned to the Amphibious Assault Forces, Task Force 52, in addition to its complement of other RCM-equipped vessels.

Beginning on February 16, 1945, the initial phases of the attack proceeded without interference from radar-equipped enemy aircraft. It was not until the night of February 19, D-Day, that the first Air Mark VI signal, with characteristics of 152/1,000/5, was intercepted on the TDY rotating antenna aboard the USS *Estes,* AGC-12. Jamming was initiated and the bogie secured his radar. From this and subsequent action, it was evident that the antijamming lessons learned by the Japanese in the Philippine invasion had not been widely disseminated. In striking contrast, U. S. naval forces were in an excellent position to put their previous experience to good use.

Approximately six radar and RCM pickets were stationed in the area, at distances of 10 to 50 miles from the island. Adequate warning necessary for the tuning of spot-jamming or barrage-jamming transmitters was easily obtained.

Protection for the vessels in the transport area was afforded by both the RCM-equipped vessels of the force and the ten or so specially prepared LCIG-RCM. Before the landing had been effected, it was customary for these latter vessels to approach close to the beach under the cover of darkness and deliver a rocket barrage. When necessary, the pretuned AN/SPT-4's which they carried were called into action as barrage jammers for Air Mark VI signals.

The enemy's reaction to jamming was, usually, that of turning off his radar, orbiting, and then returning to base. In direct contrast to experience in the Philippine operations, enemy air attacks in the transport area at Iwo Jima were not often pressed home with suicidal fury. When the enemy radar was jammed its operator appeared to conclude that his mission could not be carried out and thus returned to base with a somewhat dubious explanation for his action. The possibility that the jamming signal or signals might be used by an enemy radar operator to guide his aircraft to a suitable target seems to have been almost entirely overlooked. Naval records, up to this time, indicate only one incident in which this tactic might have been attempted. Off Iwo Jima on March 20, 1945, the USS *Indianapolis,* CA-35, intercepted and jammed a signal of the characteristic 147/750/10 which had the same bearing as an enemy raid under scrutiny on the ship's SK. The raid closed from 2,200 to 2,223K, at which time it was jammed with a TDY transmitter. At 2,237K, 4 min later, the raid broke its direct line of approach and began to orbit. After orbiting for some minutes the enemy aircraft started to close again, along the same course that it had previously followed. This course was most likely chosen because it was the one last followed, but conceivably it might have been an attempt to home on the source of the jamming signal. At any rate the enemy raid, consisting of two aircraft, was immediately engaged by the screening forces and splashed. The total number of radar-equipped enemy aircraft which attacked U. S. vessels in the region of Iwo Jima is difficult to estimate but is thought to be in the neighborhood of 10 to 15. One observer aboard the USS *Estes,* AGC-12, believes that not more than ten such attacks took place between February 16 and March 4, 1945. Later the RCM control officer was stationed aboard the USS *Eldorado,* and the USS *Auburn,* and it is believed that somewhat fewer attacks took place during the ensuing period in which the island was secured.

In the time between the invasion of Iwo Jima and that of Okinawa numerous diversionary strikes were undertaken against widely separated objectives. Jamming transmitters were called into action in almost every instance when U. S. naval forces came under attack by enemy Mark VI radars. The general conclusion at the end of this period was unanimous approval of RCM tactics and equipment. From naval records it is not difficult to discern the basis of such a conclusion. For example, the action report of the USS *Vincennes* in the period of March 20 to April 15, 1945, reads:

[redacted]

Date	Time	Location	Result
3/20	2150K	200 mi. S. East Kyushu	Bogey turned away during jamming, but picket was firing.
3/20	2215K	200 mi. S. East Kyushu	Bogey turned away during jamming, no vessel firing.
3/21	1135K	115 mi. S. East Okinawa	Bogey turned away at 8 mi. when jammed.
4/12	2037K	60 mi. East Okinawa	Two bandits turned away at 8 mi. when jammed.
4/14	1940K	95 mi. East Okinawa	Bogey turned away at 7 mi. when jammed.
4/15	0043K	100 mi. N. East Okinawa	Bogey jammed at the same time that it was taken under fire by picket. He turned away and was later splashed by a VF(N).

In planning Operation Iceberg, the invasion of the Okinawa-Gunto, RCM operational orders were prepared for the various forces of the Fifth Fleet. For the first time, such orders included intercept guards and both spot- and barrage-jamming plans. Intercept guards were arranged to cover all frequencies from 40 to 3,400 mc, but the jamming plans were limited to the Japanese airborne bands, with the emphasis on 150 to 160 mc, for the Air Mark VI radar. RCM equipment to carry out these plans was to be available in quantity. Approximately six AGC's with their elaborate RCM installations were assigned to the operation. Some 30 LCIG-RCM with Rug and Dina transmitters and amplifiers were especially prepared for barrage jamming proposed in the transport area. In addition to these specially prepared vessels, the normal RCM installation of the assigned fleet units was available. All actual RCM operations for this large group of vessels followed the general plan of PAC-70 (B).

As the operation got under way on March 26, enemy air attacks were numerous from the beginning. It is interesting to note, however, that the great proportion of the attacks were not assisted by airborne radar. The enemy either did not have a large quantity of operational radar or he deliberately ordered that it not be used. For example, the RCM control officer aboard the USS *Estes* reports:

1. The only airborne intercepts obtained during the nights of L — 7 to L + 4 day were signals from the Mark VI radar (153/1000/8). Although bogies were within the vicinity of Okinawa almost constantly during these nights few such intercepts were obtained. From a total of 36 raids in the above period, Mark VI intercepts were obtained on three of them. Signals were picked up when the bogies were 80-90 miles away and were received intermittently while they closed. No signals were heard after the enemy aircraft approached to within 15-4 miles of Okinawa. Look-through periods varied anywhere from ten seconds to six minutes, while the bogies were approaching. Periods between looks, varied in a similar manner. Such tactics indicated the enemy might be using his radar to find and then home on the island of Okinawa. Undoubtedly, he was previously informed of the fact that we could jam his set.

2. After L + 4 day Mark VI signals were heard just as infrequently although the tempo of the air raid ran about the same.

As a rough estimate one observer who was aboard the same vessel, the USS *Estes*, believes that in the 30-day period following L-day, when the troops first went ashore at Okinawa, approximately 15 Air Mark VI signals were intercepted and jammed. After this, as time went on the number of intercepts decreased. With a decrease in the total number of intercepts, new types of enemy ASV radar made their appearance. For instance, in the early morning of April 7, 1945, an airborne signal with the characteristics 210/750-1,000/15 was obtained. Possibly this intercept indicates use of the Japanese Army Taki Model 1. Because its frequency was in the same band as U. S. air-search raiders, the SC and SK, jamming was not attempted.

The exact manner in which the enemy had been directed to use his ASV-type radar is, even now, not known with certainty. It seems likely that after the initial days of the operation instructions were issued to use airborne radar at infrequent intervals in order to decrease the probability of intercept and successful jamming by U. S. forces. Although the Air Mark VI was originally intended for locating surface vessels it was probably used sometimes as a navigational device to guide attacking aircraft to the general area of an island. Furthermore there is a possibility that the receiver portion of the Air Mark VI was used to home on

1. Allied v-h-f voice transmissions.
2. Allied IFF.

SECRET

3. Enemy shore-based radars such as the Mark I Model 3.

None of these possibilities was ever definitely proved, however, and the exact navigational or homing procedures used by the enemy are uncertain.

Of particular value in interception of enemy airborne radar was the high-gain, rotating, directional antenna, familiarly known as the "TDY rotating antenna." The RCM control officer aboard the USS *Estes* singles out this particular item for comment.

> TDY rotating antenna has been of great value in intercepting enemy signals. Signals have been consistently received from enemy planes reported (by radar) at distances from 80 to greater than 100 miles. At these distances no signals were received on a dipole antenna. For example, while en route to Okinawa, RCM reported an airborne radar signal 153/1000/8 on a bearing of about 060T. One of the radar picket ships in the screen reported an enemy plane on this same bearing. From the approximate speed of the plane it was found that this signal when first intercepted was at a distance of 110 miles. When the plane was disappearing through a radar fade we were able to follow him with the TDY antenna; by dead reckoning an idea of his movements was obtained, until he again reappeared on the radar.

Thus ends the report on the role played by ship-borne countermeasures against enemy airborne radar in the invasion of Okinawa. As in any countermeasures operation the determination of its success in concrete terms is extremely difficult. It will be obvious, though, that numerous night air attacks were either prevented or made less effective. In spite of the fact that electronic jamming will not stop a Kamikaze pilot, RCM assisted in preventing the large number of fleet units lost at Okinawa from being larger still.

15.5.5

Miscellaneous

Since this chapter is principally concerned with the operational use of radar countermeasures in World War II, detailed discussion of communication countermeasures, guided missile countermeasures, and AJ techniques has been avoided. Pacific naval operations, however, involved considerable effort in each of these fields. For these reasons, a brief reference indicating the status and plans in these fields as of April 22, 1945, is included below.

Communication Countermeasures

PAC-70 (B) directs that

> fleet commanders, the OTC, and landing force commanders having qualified personnel will intercept enemy circuits and take action in *tactical* situations. Ordinarily jamming has less military value than the information which may be obtained from interception.
>
> The approved type allowances of communication countermeasures equipment calls for radio intercept and jamming equipment of AGC's and fleet and major task force flagships only. Communication countermeasures activities in the Pacific Ocean Areas have been purposefully limited to keep radio jamming and deception operations under the direction, supervision, and control

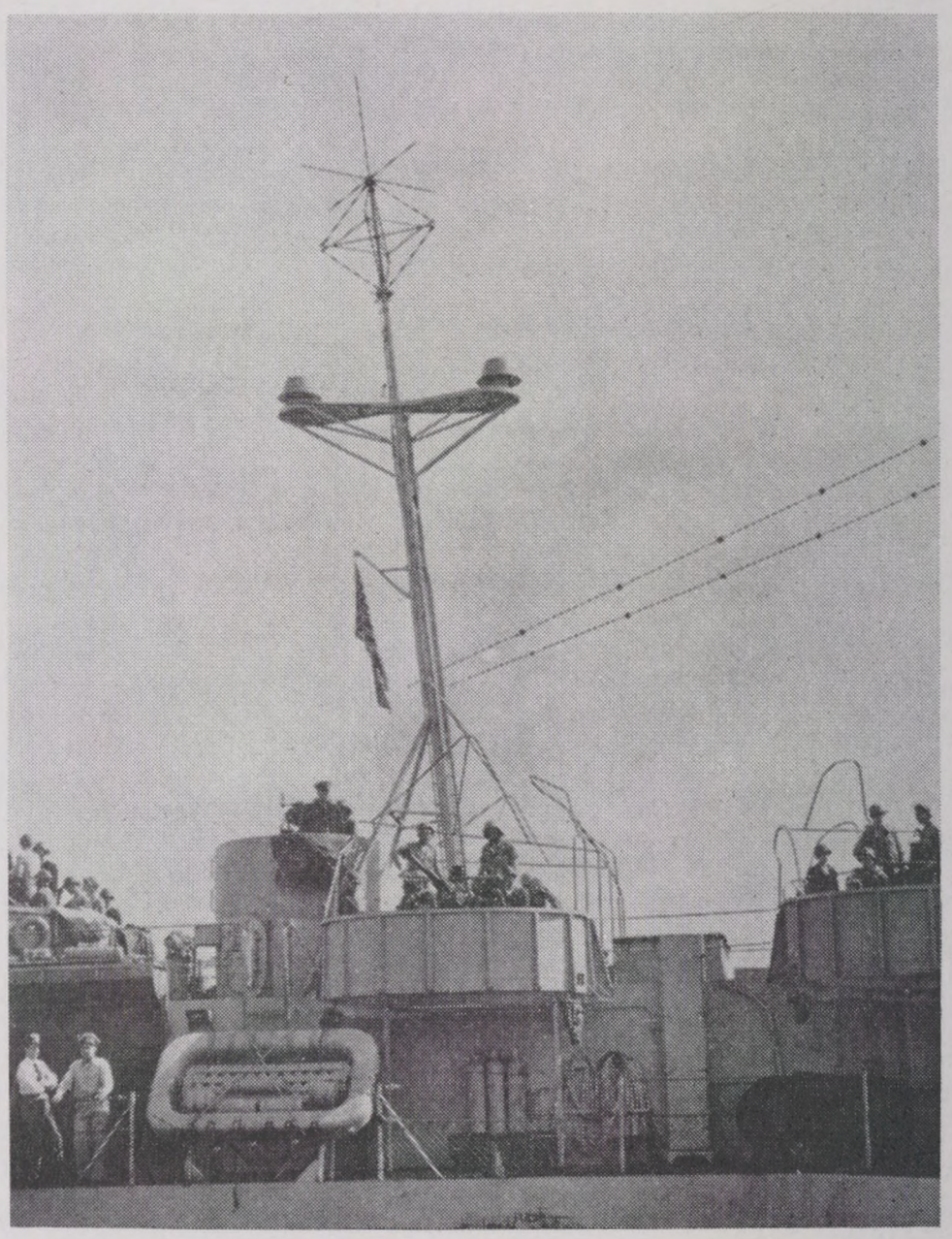


FIGURE 8. Typical installation on the aftermast of a destroyer of DBM-1, high- and low-frequency, rotating-head, direction-finding antennas.

> of those echelon commanders who at the same time have the immediate services of the communication security and radio intelligence organizations.

Radar Antijamming

PAC-70 (B) directs all commands to insure

> that radar and CIC personnel receive intensive training in radar anti-jamming. Maximum use of AJ techniques and equipments shall be made in an endeavor to combat

any enemy countermeasures and to read through any interference caused by friendly jamming operation.

Guided Missile Countermeasures

To date (April 22, 1945) there has been no GMCM activity in the Pacific Ocean Areas because the Japanese have substituted the human mind and body for the more conventional "radio-control" features normally favored by other nations for guided missiles work. There is, however, close liaison between the Japanese and Germans in the electronic field and this fact, coupled with the acute pilot-shortage which might be caused by such costly attrition as that occasioned by suicide tactics, may force the Japanese into an attempt to follow the German guided missiles program. To prepare for such an eventuality three GMCM Investigational Groups, composed of GMCM personnel from the European Theater who have received additional refresher training at SPS, have been formed and assigned to ComDesPac. These groups, one of which is already operating, accompany various task forces and maintain a continual search with highly-specialized equipment for any guided missiles control signals, recording for analysis and reporting all unidentified or suspicious intercepts.

Ten destroyer escorts are being fitted with GMCM intercept and jamming equipment as a further standby measure. If it becomes necessary to combat a full-scale Japanese guided missiles program, ten more GMCM Investigational Groups will be requested from CNO and assigned to these ten DE's. In addition, a supply of GMCM jamming and monitoring equipment will be maintained in various material pools in the Pacific Ocean Areas to be used for immediate installations in major combatant ships if necessity arises. "Crash" instruction will be conducted, in this event, both at SPS and at the Pacific Fleet Radar Center to provide radio personnel from the Fleet trained to operate this GMCM equipment.

15.6 RCM IN THE U. S. AIR FORCES

15.6.1 The Operational Problem

There were marked differences between the RCM program in the Pacific Theaters of Operations and those in the European and Mediterranean Theaters of Operations, the most outstanding being the infinitely greater reconnaissance problem encountered in the Pacific. U. S. forces in the ETO and MTO were indeed fortunate in having available all the information of German radar operations and developments that the British had been gathering since 1939. The line of approach to the planning of equipment requirements and operational tactics was at least partially indicated. This was not so in the Pacific Theaters of Operations. It was a long job, requiring many months of intensive RCM reconnaissance work, to establish the types and functions of radars being used by the Japanese. Merely the effect of the distances between the various areas within the theater required that complete reconnaissance of each area be accomplished before offensive operations in that area could be undertaken. Since the progress in the Pacific was from the newly won outlying areas toward the well-established inner defenses of the Japanese home islands, the best defenses were not encountered until the 20th bomber Command began operations in June 1944. This required that offensive countermeasures, where necessary, be initiated almost immediately after the operational use of GL and SLC radar had been definitely established and its characteristics known.

RCM operations in the Pacific were different from those in Europe in another respect. The similarity of RCM problems in the ETO and MTO made the same tactics feasible in both places, whereas in the Pacific major emphasis on different phases of RCM activities appeared in the different parts of the theater. For instance, in the Southwest Pacific Area, considerable emphasis was placed on attacking enemy radars ("radar busting") and deception activities. Because of the small number of radars covering a given area, it was possible to gain a great tactical advantage by making one of them useless by one means or the other. On the other hand, in the Nanpo Shoto and Nansei Shoto island chains radar busting and deceptions would have been much less fruitful because of the high density of radars on all frequencies and the prevalence of radar-equipped picket boats. Gun-laying radar was never found in any quantity in the Northern Pacific and CBI areas, and no jamming equipment was ever employed. In the Philippines and Formosa, GL and SLC radar appeared in small quantity, and over the Japanese home islands considerably greater numbers of gun-laying and/or searchlight-control radars appeared, both areas requiring the use of offensive RCM. It should be reiterated that the Japanese GL/SLC radar was never good enough to constitute a serious threat to the success of operations.

SECRET

A few attempts were made to reduce fighter opposition by deception and evasion both in the Southwest Pacific and over the Japanese home islands, but no wide-scale effort to avoid fighters, such as was necessary at one time in the ETO, was ever attempted in the Pacific. Fighter opposition in the spring and summer of 1945 was never great.

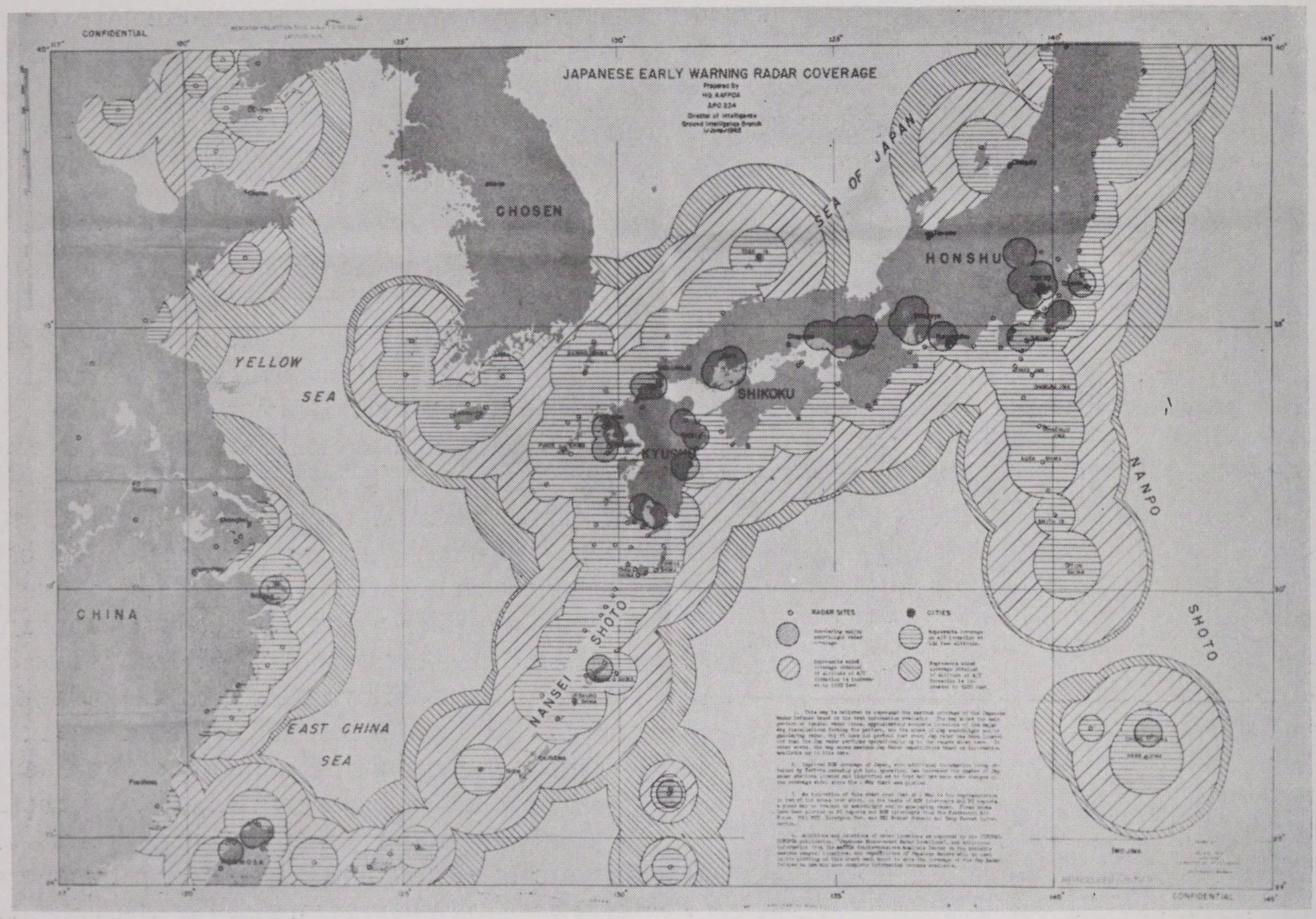


FIGURE 9. Japanese radar-coverage map prepared from the search results of aircraft, surface vessels, and submarines. Coverage of early-warning, gun-laying, and searchlight-control radar is indicated.

15.6.2 Capabilities and Limitations of the RCM Available

In the Pacific Theater, as in the European Theater of Operations, the two main lines of attack against the enemy radar involved the use of Window and electronic jammers. Because of the differences between the Japanese and German radars, however, the type of Window and electronic jamming employed had to be different. Instead of bundles containing a large number of small dipoles cut to the frequencies of the enemy radar, the type of Window employed in the Pacific was in the form of a long aluminum strip called Rope. This consisted of a ribbon of aluminum about ½ in. wide and 400 ft long, tied to a nylon leader about 15 ft long. At the end of the nylon ribbon, a small chute or a cardboard tab was attached. When the Rope was thrown out of the plane, the small parachute or the cardboard tab was caught in the slip stream and the ribbon unwound itself. Rope completely unwound falls at the rate of about 600 ft a minute. Depending upon the aircraft and upon the frequencies of the enemy radar against which it works, a bundle containing three rolls of Rope represented an echo comparable, if not equal, to the echo given by a heavy bomber. Since Rope is an "untuned" reflector, it was effective against all Japanese

SECRET

radars simultaneously, especially since the majority of enemy radars operated below 200 mc. Window, employing bundles of small dipoles, was used only to a very limited extent.

Electronic jamming employed transmitters based on the same fundamental principle of operation as those used in Europe, but the different frequencies involved made new sets necessary. These sets had to cover the frequency band from 70 to about 220 mc. No one set was available which was capable of covering the whole enemy band. For this reason, three types of transmitters were employed in the Pacific Theater: APT-1 (Dina); APQ-2 (Rug); and ARQ-8 (l-f Dina). Without going into the technical differences between these three sets, it might be mentioned that the latter, the ARQ-8, was an l-f set capable of covering frequencies from 50 to about 100 mc; that Dina could be employed above 100 mc; and that Rug had to be modified to cover frequencies below 200 mc.

Window

The observation made in the paragraph entitled "Chaff" under Section 14.5.2 in the previous chapter can be extended to Rope. Some differences exist, however, because of the different type of operation, the different types of formation, and the different types of radar. When Rope was dispensed by a formation of tactical aircraft, the full protection that Rope could give to the formation flying near or within a Rope trail was not available. The reason for this was, of course, that very seldom did more than one formation attack the same target within an interval of time short enough to make the full protection of Rope available to the trailing formations. In this case, the effect of Rope was one of introducing confusion into the enemy's radar picture so as to make it difficult for the operator to locate the target and track it continuously. The use of Rope by the B-29's was very similar to the use of Chaff by the 8th and 15th Air Forces. B-29's flew in formations comparable in size to the formations flown in Europe. It must be added, however, that B-29's also flew night missions with single aircraft and in this case, more than for daylight formation flights, it was difficult for the radar operator to locate the Window trail and to track their leading edges except for the period when the first aircraft were flying over the target area.

In Europe, the RAF repeatedly used Chaff as a means of deception. The planes of the Bomber Command dropped Chaff during their whole course at a rate much slower than the one employed by the American Air Forces. Whereas the American Air Forces in Europe dropped Chaff only on or near the target area, the RAF laid trails of Chaff during the whole penetration course and part of the withdrawal. The Bomber Command employed small forces dropping large amounts of Chaff to simulate attacks where no major attack was going to take place, or at a time different from the real one. Tactics similar to these were occasionally employed in the Pacific Theater by several of the air forces. The effectiveness of these deception missions cannot be evaluated, in general, but some information is available and will be discussed in detail in the following sections of this report which refer to the activities of the particular air forces.

Rope is particularly useful as a deception measure because it covers a wide band of frequencies. Especially against an enemy whose radar network had to cover very wide areas and whose approaches were always from the sea, deception maneuvers appeared attractive. However, no deception maneuvers of the order of magnitude employed in Europe in the invasion of Normandy or of southern France were attempted.

The Japanese did not develop any AJ device comparable to the ones developed by the Germans as a defense against the Allied use of Window. For this reason, despite the fact that at the time of the writing of this report no direct intelligence is available on the effectiveness of Allied RCM on the Japanese radar, it appears likely that Rope was effective in throwing the enemy radar off balance. Operational reports from both strategic and tactical air forces reported successful evasion of enemy searchlights by Allied aircraft.

Electronic Jamming

The two types of electronic jamming described and discussed in the previous chapter

SECRET

applied also in the Pacific Theater. The advantages and disadvantages of spot and barrage jamming were the same in the two theaters. It must be mentioned, however, that, for a tactical air force which attacked a target with only one or two radars, it would have been very uneconomical to employ a barrage type of jamming. For this reason, spot jamming was employed in practically all the tactical air forces. In some cases, the knowledge of the enemy radar was good enough to enable the jammers to be pretuned on the ground to the frequency or frequencies that the dangerous radar or radars were known to have.

In the case of the 21st Bomber Command, on the contrary, the analogy with European Theaters was practically complete, and barrage jamming and spot jamming were used in combination in a way very similar to the one already described with the 8th and 15th Air Forces. The operations of the 21st Bomber Command will be described later in detail. It must be mentioned here, however, that the weaknesses of the Japanese radar were such as to make it possible to employ in the Pacific a method which had been used by the RAF against the German ground-controlled-interception radar but which could not be duplicated in Europe by the AAF against the German gun-laying radar. By this it is meant that the 21st Bomber Command found it possible to use special aircraft flying over the target area, continuously jamming these enemy radar sets and dropping Rope. This was done during night operations only; the reason why this could not be done in Europe was that the number of special aircraft necessary to jam the German Wurzburg would have been prohibitive because of the narrow beamwidth and wide frequency spread of this radar set. The use of these special aircraft, called Porcupines, will be discussed in detail later.

Except for the observations made above, all the considerations listed in the previous chapter in the paragraph on "Carpets" under Section 14.5.2 about the relative merits of barrage and spot jamming, training of spot-jamming operators, danger of the enemy DF-ing on Allied jammers as a means of laying its guns—all apply to the Pacific Theater unchanged.

15.6.3 Operational Use of RCM in Northern Pacific Theater

Search and Investigation

The Northern Pacific Theater was the first theater of operations in which any RCM activity took place. After the Japanese were forcibly removed from the Aleutians, the theater activities were very much reduced in scope. During both the active and inactive phases of operations, the RCM work was limited to search and investigation.

In the fall of 1942, photo-reconnaissance of the Kiska area revealed what might be a radar station. It was felt that an RCM reconnaissance aircraft would be valuable for confirming this. As a result, an offer of a Ferret was made to the 11th Air Force, and, on the advice of the Operational Analysis Section, the Ferret was requested by the theater. Thus, work on Ferret I was initiated. The B-24D was outfitted at East Boston and at Wright Field in December 1942 under the supervision of RRL personnel. The Ferret was equipped with the newest reconnaissance equipment available at that time. No DF antennas were available, but stubs were mounted on the nose for left-right homing.

Ferret I arrived in the theater in January 1943 and began operation out of Adak. Two specially trained RCM officers came to the theater with Ferret I and operated the reconnaissance equipment on search missions. The Ferret was also used for weather and radar reconnaissance work. From January to March, missions were flown west from Adak to Kiska, Attu, and Paramushiru. Two Mark I Model 1 radars on Kiska were located roughly about 500 ft above Kiska Harbor. The Ferret proceeded to log the characteristics and plot the coverage of the two radars. After March, Ferret I made occasional flights to check periodically on the radars on Kiska, but the majority of its time was spent in weather reconnaissance work. It was called into service for RCM reconnaissance again shortly before the invasion of Kiska in August 1943, when it was used to augment the search activities of Beaver I. During these searches, a 300-mc signal was logged, which later proved to be spurious, and an APQ-2 was

rushed to the theater in preparation for jamming this radar if necessary.

Eleventh Air Force RCM activity was dormant until the first part of 1945, when a new Ferret I arrived in the theater. This Ferret was attached to the 40th Bomb Squadron (H) and flew its first mission on January 20, 1945. This Ferret was equipped with the latest reconnaissance equipment. Routine searches were made in the vicinity of Paramushiru and the northern Kuril Islands and the same type of EW radars encountered in other theaters were heard. On April 18, 1945, in the vicinity of Shimusu and Paramushiru, Ferret I made its first intercept of a radar of Mark TA Model 3 characteristics. This radar was presumed to be at the Kataoka Naval Base and was associated with flak through undercast. However, the flak was inaccurate and did not constitute a problem. Further missions mapped all the radars in the area, but flak, and especially flak against unseen targets, was never accurate enough to cause concern.

15.6.4 Operational Use of RCM in the Southwest Pacific Theater

RCM Organization

The organization initially responsible for all RCM in the Southwest Pacific Area was Section 22, an Allied inter-Service organization in General Headquarters [GHQ]. It consisted of a headquarters and a number of "field units." The headquarters planned and coordinated RCM activities, analyzed and disseminated RCM intelligence, and requisitioned and assigned RCM personnel and equipment. The field units, as the name implies, gathered data and either carried out, or cooperated in, the execution of RCM plans. This arrangement prevailed during what might be called the investigational period of SWPA RCM, lasting from late 1943 to, roughly speaking, the beginning of 1945. In this period, Japanese radar in the theater grew from insignificance to the point where it became a threat to operations. Through the activities of Section 22 in this period, the Allies were able to keep informed of Japanese radar developments and found themselves at least partially prepared to take measures against Japanese radar when they became desirable.

As time went on, the war in the SWPA grew on both sides in scope and modernity, and emphasis in RCM gradually shifted from intelligence to jamming and physical attack. It was inevitable that in the short-range planning of RCM activities the field units should more and more work directly with the operational commands involved (such as the Seventh Fleet and the Fifth Air Force), and the field units gradually assumed a free hand in this respect. However, Section 22 retained its other prerogatives —long-range RCM planning, including supply of equipment and personnel, and intelligence coordination.

As of May 1, 1945, Section 22 relinquished operational control of Army Air Force RCM to the Far East Air Forces [FEAF] and of naval RCM to the 7th Fleet. With this transfer, the field units which had been working with the Air Forces and Navy were dissolved, and their personnel and equipment were turned over to the respective commands. Day to day operations continued just as before. Section 22 remained as the central RCM intelligence organization of the theater and continued to control Army Ground Force RCM, which was principally concerned with communications.

Search and Intelligence

Two sources of information on Japanese radar were available: intelligence reports and intercepts by search equipment. The former originated chiefly with captured material and prisoner of war interrogations. As Allied forces advanced, more and more Japanese equipment and documents were captured. The information gained was invaluable. Even more benefit could have been derived from the booty had there been in the theater a well-equipped group of scientists to perform detailed analyses. In this way, the results could have been used immediately.

The first attempts at carrying out radar search were made from strike aircraft, submarines, and motor torpedo boats. This type of search grew in scope as World War II advanced, and from the middle of 1944 on it pro-

vided much reliable data on Japanese radar. It was handicapped in the beginning by the absence of DF-ing facilities (and the navigational aids required for their effective use) and by the fact that the only receiver available had spurious responses so that the number of radar frequencies reported considerably exceeded the number later found to be employed by the enemy. Nevertheless, during 1943 some coverage of the areas immediately north and west of Australia was obtained, and a limited coverage of certain regions in the Philippines, China Sea, and Malay Peninsula was accomplished by submarine.

The need for special radar reconnaissance aircraft, Ferrets, became increasingly apparent. Even with the best of equipment, strike aircraft have some inevitable limitations. They can only cover the areas swept out by strikes and so fail to give advance information for use in planning future activities. They are not free to navigate in such a way as to obtain the best RCM information; and the amount of special gear that they can carry is limited. Thus, adequate coverage of Japanese air-warning radar could only be provided by Ferrets. By January 1944, two USAAF B-24 Ferrets, which had been fitted out in the United States, were operating from New Guinea bases. During the next 2 months, 32 Ferret missions were completed in the Bismarck Sea area. Specific searches were made around the Admiralty Islands and Hollandia, New Guinea, in preparation for the forthcoming Allied landings.

By July 1944, the investigation of the Northwest Pacific Area (i.e., a region bounded by Borneo, Java, Australia, and New Guinea) was completed. The acquisition of Owi made it possible to obtain coverage farther north, so that Morotai and the Palaus were well surveyed before the landings there (September 15, 1944). The next step was the Philippines, and coverage up to Manila was provided. A few days before the Leyte invasion (October 20, 1944), existence of a radar on Suluan Island, commanding the entrance to Leyte Gulf, was confirmed, and as a result a party of Rangers was sent in to destroy this radar at the start of the invasion.

During one of the Philippine flights a Ferret made the first unequivocal intercept of Japanese ship-borne radar by obtaining direction-finding bearings which were coincident with a ship plot on the SCR-717.

In the winter of 1944-45, the two Ferrets began to show signs of wear. Nevertheless, the coverage of the Philippines was completed and some Formosa data were obtained. One replacement Ferret finally arrived in February 1945. The coverage of Formosa was completed, and the Asiatic coast, from Saigon to Shanghai, was mapped out. A second replacement Ferret arrived in April. A number of flights to Kyushu were also made before World War II ended.

There were some other aircraft in the theater assigned to full-time radar investigation. A Navy Catalina under the operational control of Section 22 was fitted with search gear in the theater and began operations in May 1944. In the absence of a DF antenna, a pair of symmetrically placed cones was used to DF by homing. In this way, a number of EW stations in New Guinea, Halmahera, and the Philippines were located. During the second battle of the Philippines (October 26, 1944), the PBY detected and located by its RCM gear a Japanese task force moving through the Camotes Sea and reported it at once. Delay in retransmission of the message prevented our naval forces from using this vital information. This PBY was later replaced by another, also fitted out in the theater, whose RCM complement rivaled those of the Ferrets. It included an APA-24 DF antenna. This Catalina was particularly valuable at the height of the Philippine campaign, when the two B-24 Ferrets were operating on a reduced basis.

Another Ferret was the so-called Armed Ferret of the Thirteenth Air Force, a B-24 fitted out in the theater, early in 1945, with a great variety of RCM equipment. It had, in addition to the normal search gear, homing equipment for use in radar busting, and jamming antennas. The arrangement of the equipment permitted use of the plane in normal strikes with full bomb load as well as on lone reconnaissance. The personnel of this plane worked out a new technique of locating radars using a camera. This photographic technique, which was quite successful, was obviously usable only under conditions of

overwhelming air superiority, when unescorted daylight flights were permissible.

In view of the necessity, pointed out below, of intercept both in strikes and on special reconnaissance flights, the Armed Ferret appears to be closest to the ideal RCM installation. It combines the advantages of a standard combat plane with those of a flying laboratory.

Concurrently with all this special reconnaissance, search was being carried out from strike planes. It was realized that only by search during strikes could it be determined how the Japanese used their radar against enemy aircraft and whether they had GL, SLC, or GCI in operation. For this reason, before strike planes were adequately equipped with search gear, the Ferrets accompanied several strike missions. In only one instance was any short-range radar heard, a probable GL or SLC radar at Balikpapan, but it was discovered that some EW radars came on the air only when a strike was under way. Thus, search coordinated with strikes was required even for complete coverage of early-warning radars alone.

By the middle of 1944, a fair supply of APR-1's and APA-6 pulse analyzers was on hand. The 380th and 90th Bomb Groups (H) of the 5th Air Force, which engaged in daylight strategic bombing, flew at least one B-24 equipped with receiver and pulse analyzer on each strike. On January 13, 1945, a 200-mc high prf signal was heard tracking the formation in the target area. Search now became more than a precautionary measure, and all four B-24 groups of the Fifth Air Force were soon carrying intercept receivers on their missions to targets with heavy flak. Consistent use of both 200-mc and 79-mc GL radars by the Japanese on Formosa was revealed, and 200-mc GL radars were also located at Ambon and Saigon.

January also saw the beginning of H2X operations in the theater. The H2X-equipped planes were first used simply as lone night bombers. One of them had some intercept gear and was able to check on the use of radar for SLC in Formosa. As anticipated from the October 1944 Balikpapan intercepts and from intelligence 200-mc SLC radar was used, and beginning on January 22 diversionary tactics were introduced as a countermeasure.

Another class of strike plane was the radar-equipped B-24's that engaged in antishipping patrols over the vast expanse of the theater. Outstanding in RCM was the 868th Squadron of the 13th Air Force, which started intercept work in the middle of 1944. In October 1944, a B-24 of this squadron confirmed the use for SLC of a 200-mc radar at Balikpapan that had been heard previously by a Ferret, and Chaff (CHB-1) was used against it, with undetermined effect. In this same month, some homing antennas were constructed in the squadron and installed; and Japanese radars were designated as permissible secondary targets for this squadron. As time went on, and the number of lucrative shipping targets diminished, the detection, location, and destruction of Japanese radars became a major activity. An example of the "perfect" RCM mission occurred on November 3, 1944, when one of these B-24's intercepted, homed on, then photographed, and finally bombed and strafed an enemy radar on Sibago Island (Sulu Archipelago).

Mention should also be made of the B-25 "radar busters" of the Thirteenth and Fifth Air Forces, which located radars as well as attacked them.

RCM against Early-Warning Radar

This section and the following one are concerned with the use made of the information gathered on Japanese radar, as described in the preceding section.

The only practical countermeasures against EW radar were evasion, deception, and destruction.

Location of the radars made it possible to estimate their heights above the water (almost all the radars were coastal); from their known capabilities, the ranges could then be calculated at which, under average conditions, planes at various heights could be detected and the shadows due to terrain features could be estimated. Coverage charts, showing these contours of detection, were issued regularly and were used in various ways: to lay out the courses of bombing missions that lacked fighter escort; to determine the courses and altitudes to be used by mine-laying planes, as in the mining of Balikpapan Harbor by Catalinas in the summer of

SECRET

1944; to do the same for the Air-Sea Rescue Catalinas that picked up flyers from enemy territory and carried supplies to guerrillas; and to plan low-altitude attacks on the radars themselves. The charts were also used to define areas in which IFF silence was to be maintained. This was necessitated by the fact that some of the Japanese Mark I Model 3 radars operated in the frequency range of Allied IFF. The consequent triggering of the IFF would increase the range of the enemy radar.

Deception tactics were used in connection with a number of special operations. The wide dispersion of Japanese radars in the theater made it possible to carry out these deceptions with the very limited means available, though the slowness of the enemy in reacting to anything out of the ordinary and the lack of coordination between his various headquarters tended to reduce the operational value of any deception. In coordination with the Leyte landing (October 20, 1944), the two Ferrets and an additional B-24 used Dinas and Chaff to simulate the screening of air operations against Mindanao, with uncertain results.

A second try at deception was made on January 4-5, 1945, in connection with the landing on Luzon 4 days later. Here the attempt was to simulate the approach toward Legaspi of a naval bombardment force with air cover. The limited naval and air facilities in the theater made it necessary to attempt the job with only one plane, one of the Ferrets, which circled about, advancing at an average speed of 20 k, all the time dropping Rope. Just how the Japanese interpreted their radar plots is not known.

An example of a mission where clear-cut success was obtained is an operation undertaken by the Thirteenth Air Force early in 1945. Here use was made of the Japanese practice of shutting down when an unidentified aircraft closed to within about 5 miles. It was desired to bomb an airfield on Halmahera, all the approaches to which were covered by a particular EW radar. A "heckling" plane made passes at this radar for about an hour, causing it to stay off the air; meanwhile, the strike reached the target undetected and did not receive any fire till it was on the way out. Several other successful heckling operations were carried out later.

Physical attack on enemy EW radars was a major activity during the last year of the war in the SWPA. The dispersion of the Japanese positions, and their bad supply and training situation, made the Japanese very vulnerable to this kind of countermeasure. In a number of cases the radar busting had immediate tactical value. Allied "leapfrogging" had left the Japanese EW net in the Indies practically intact. On very long-range raids like those to Balikpapan and Surabaya no feinting was possible, and the Japanese could have obtained early enough warning to shift fighters to the target area. Elimination of the radars which covered the route was therefore desirable. Radar busting was, on the other hand, out of the question in Formosa, because of the denseness of the radar net on this highly developed island. It was never practiced against GL and SLC radars because of the danger involved.

The attacks were first made by fighters or attack bombers after the station had previously been located by an RCM plane. Later on, the B-24's of the 868th Squadron and the Navy's PB4Y-1's combined the functions of search and attack. Finally, several B-25's were fitted with receivers and DF antennas, and assigned exclusively to radar busting. The Japanese practice of shutting down when being homed on made necessary an approach on the deck (at a very low level) to delay detection, at maximum speed. The B-25 was the plane best suited for the job; the A-26 would, no doubt, have been even better when it became available.

RCM against GL and SLC Radar

In the subsection entitled "Surface Vessels" under Section 15.5.4 it has already been told how gun-laying radars put in their appearance on Luzon and Formosa and how countermeasures were immediately started.

The jamming of the GL at Clark Field was cut short by occupation of the area, and the main jamming effort in the SWPA was thenceforth against Formosa. From the end of January 1945 to the end of June, when it had been rather thoroughly bombed out, Formosa was the principal target of the 5th Air Force. The activities involving RCM were of two sorts: day bombing by tight group formations of 18

to 24 planes (on big occasions several groups might bomb together), and night bombing by single radar-equipped planes.

In the day operations, altitudes ranged from 10,000 to 15,000 ft. Visual bomb runs, initially several minutes long, were soon shortened to less than a minute. Fighter escort was provided, in case the Japanese should decide to use their

ous Marks, Models, and Modifications that might have been used) and the 78-mc band (Mark TA Model 3). They tracked Allied aircraft under all weather conditions, but whether they were used to control fire when optical control was possible was never decided. There is no doubt of their use for fire control under blind conditions; the mission of February 18, 1945, to

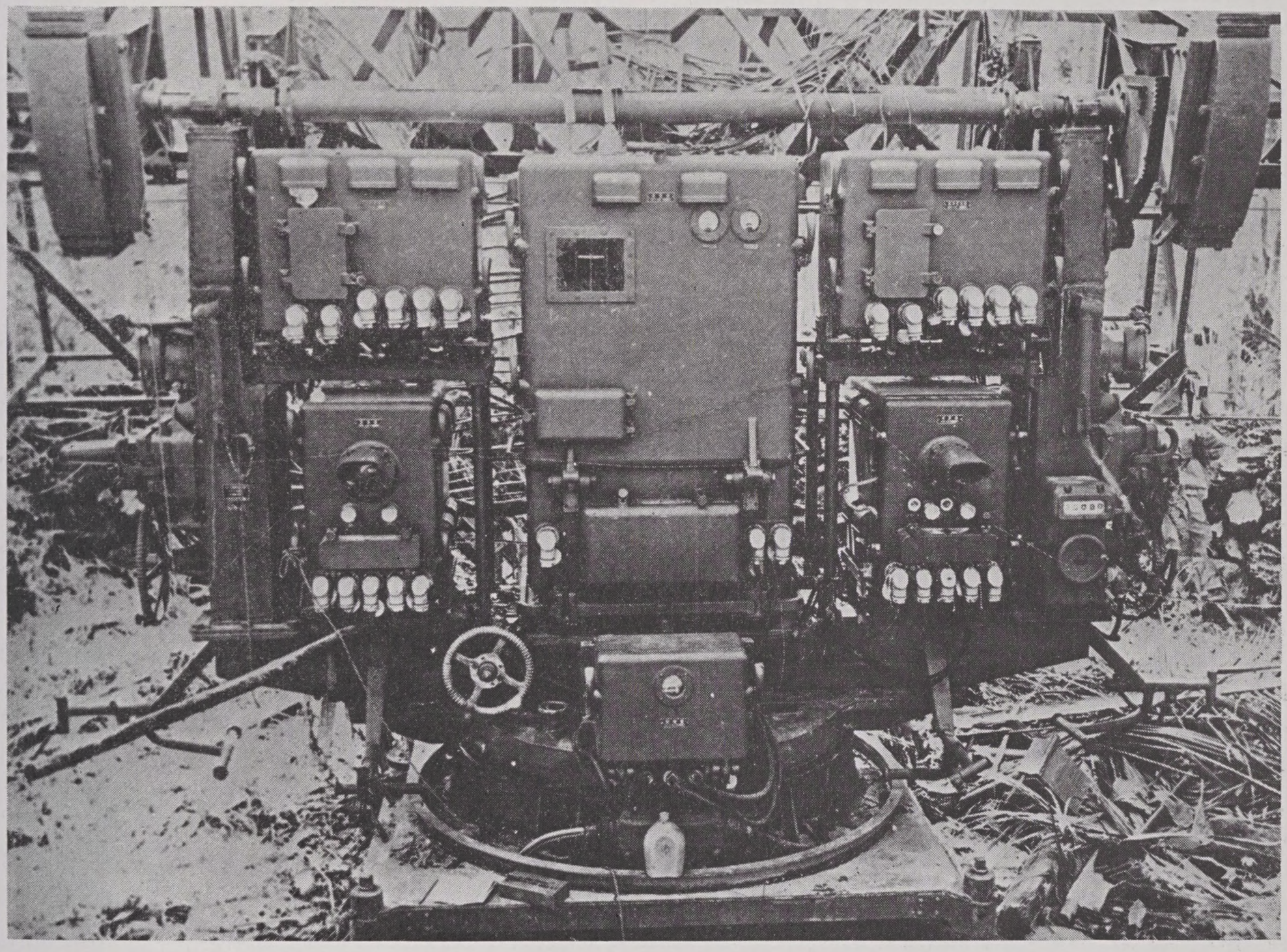


FIGURE 10. Captured Japanese gun-laying and searchlight-control radar of the Mark IV type. Note the similarity between this equipment and the U.S. SCR-268 from which it was copied.

large fighter strength in Formosa. The fighters never did come up, except against stragglers, and the escort could well have busied itself dropping Rope, had automatic dispensers for P-38's been available. The Formosa weather—undercast was the rule—made the use of H2X necessary and about one-half of the missions were effectively blind. The H2X bomb runs lasted several minutes.

The GL radars operated in the 200-mc band (it never was possible to disentangle the vari-

Takao, when the lead ship was hit immediately after the formation emerged from over 10/10 undercast was a case in point. The formation had been tracked on its constant course for several minutes by both a 79-mc and a 201-mc radar, and the shells must have been fired before it came into the open. No jammers were carried on this mission.

The strongest targets had one radar in each band; the lesser ones had just one radar. The number of guns per target ranged from 25 to

75; and the total damage rate (almost all the missions had some RCM protection) was about 20 per cent. This rate refers to the percentage of planes holed out of all those shot at.

The one-wave tactics prevented reliance on Window to the extent customary in Europe, where the Chaff laid by the first two or three hundred planes infested the target area to the great benefit of the subsequent hundreds. In the Pacific, where the one or two radars were approached practically head on, Window would, in the long run, have had little self-screening value. It was, therefore, used as a supplement to electronic jamming, the main reliance being put on the latter.

The Dina and the ARQ-8 were used against the 200-mc and 78-mc sets respectively; 25 of the former were on hand in January 1945, and 25 of the latter, ordered on emergency requisition in January, arrived early in March. The small number of radars per target made this small number of jammers, distributed on the basis of four of each per group, adequate. A kind of spot jamming was used. An APR-1 (or later APR-4) was installed in each jamming plane, and it and the jammers (preset to the expected frequencies) were attended by an RCM operator. Search was carried out en route. On the approach to the target, it was concentrated on high prf signals in the known GL bands. As soon as one was heard tracking, the jammer was switched on and retuned from its preset value if necessary. The operator monitored both radar and jammer until the group was out of the target area, when the jammer was turned off.

The night missions to Formosa were carried out by H2X ships detached from the 90th Bomb Group and by SCR-717B-equipped LAB planes of the 63rd Squadron (43rd Group). Difficulty was experienced from 200-mc SLC, and starting on January 22, 1945, these planes began to use Rope. The original tactic was for the planes to dispense a single roll and take evasive action whenever caught in a light. Later on, the quantities of Rope used were increased.

The zone of operations of the Thirteenth Air Force at this time lay to the south of Manila, and GL jamming was not yet needed. The only SLC jamming carried out by the Thirteenth Air Force, other than the October 1944 Chaff effort over Balikpapan, was in connection with a series of strikes by the 868th Squadron against Surabaya. The raids, each one carried out differently, culminated in the show of May 7-8, 1945. Four planes, including the Armed Ferret functioning as a special jammer, went in at between 10,000 and 12,000 ft to bomb harbor installations and drop Rope for the protection of the six planes which, about 10 min later, came in low at between 300 and 1,000 ft to attack ships. The former, as hoped, attracted the searchlights, permitting the low planes to make undisturbed runs. All of the high planes but the Armed Ferret had difficulty eluding the lights; the Ferret had only to turn on its Dinas, tuned to the 200-mc signal being heard, to be able to evade easily the lights that were holding it. It circled the target, attracting searchlights by turning on its landing lights and evading them again by turning on its jammers, until all the other planes had made their getaway, and then it returned safely to base.

Early in the summer of 1945, the Pacific commands were reorganized, and the Seventh Air Force (three B-24 Groups) was joined with the Fifth and Thirteenth under FEAF. The B-24 strength of FEAF, based on Okinawa, was to be considerably expanded, and, in addition, a B-32 group, the 312th, was functioning under it. FEAF was to concentrate its strategic bombing on Kyushu, with attention also being given to the China coast. Large quantities of RCM equipment were beginning to arrive, and the goal of 16 Group A jamming and search installations per group, four of them to include DF antennas, was being reached.

Miscellaneous RCM Activities

In the mining of Manila Harbor, December 14-15, 1944, RCM was directed against both EW and SLC radars. Twenty-four RAAF PBY's, in two flights of twelve, mined Manila Harbor from 400 ft, with no loss or damage due to enemy action, despite the fact that the mission had been generally regarded as suicidal. The protection was provided by the PBY Ferret, flying at 10,000 ft and using three jamming transmitters (two APT-1's, one APT-3) and a large quantity of Rope (CHR-2), and by an

RAAF PBY, flying at 4,000 to 5,000 ft and also sowing Rope. A total of 16 signals in the 100-, 150-, and 200-mc bands were jammed, and intermittent look-throughs showed that six of the stations were shut down for more than 30 min. The intercepts also showed that the radars still on the air were sweeping the Rope areas and the jamming plane in a confused manner. Antiaircraft fire and searchlights were wild.

The Japanese used Window, decoys, and very little electronic jamming (or probably none) against our radars at various times, the greatest use being made of Window cut for 200 mc. Our countermeasure was an AJ training program, conducted principally by a field unit of Section 22. This troupe, which first used a Hudson and later a C-47 airplane, went from base to base as the need arose. It used Dinas (APT-1's), Mandrels (APT-3's), Rugs (APQ-2's), and sine wave-modulated jammers, together with Chaff and Rope. Lectures and motion pictures on the ground went with the demonstrations. The training proved to be of great value in reducing the radar personnel's learning time in combat.

Effectiveness of the RCM

The flak damage rate of the B-24's over Formosa—where the enemy used GL radar and we used RCM and where a large fraction of the missions were blind—was about the same as that experienced earlier in visual missions over Rabaul and Truk, where there was never any evidence of Japanese GL. Whether the Formosa damage rate would have been higher without RCM will never be known. But there is definite evidence that our jamming seriously interfered with the operation of the Japanese radars and that it therefore tended to undermine Japanese confidence in this new weapon. In at least three cases, Japanese radars went off the air when our jamming transmitters were turned on. In other cases, the radars being jammed proceeded to sweep, indicating our success in preventing tracking. Further evidence of the technical effectiveness of the RCM is found in the introduction of AJ measures by the Japanese. They gave up their practice of starting tracking with the Mark TA Model 3 at extreme range—which had given us ample time to retune the ARQ-8's if necessary—and only turned these sets on at the beginning of the bombing run. There was also some indication of frequency shifts by the 200-mc radars, in order to evade the electronic jamming.

No further conclusions on the effectiveness of the GL jamming can be drawn until post-hostilities intelligence from Japan is received.

The Surabaya and Manila operations illustrate the tactical benefit that can be derived from imaginative use of RCM against EW and SLC in night operations. The use made of heckling planes shows how RCM against EW can be of value even under visual conditions.

Radar busting not only restricted the overall performance of the enemy EW net but also had immediate tactical value in some operations, such as the raids on Surabaya. Experience showed that radar busting alone could not be counted upon to destroy all EW radars in any particular area; the combination of physical attack with jamming and deception was far more effective than either by itself.

The detection of the Japanese task force in the Camotes Sea by the PBY Ferret illustrates the immediate tactical value of radar reconnaissance.

15.6.5 Operational Use of RCM in the India-Burma and China Theaters

Organization

In the India-Burma and China Theaters there were three American air forces. The Fourteenth Air Force in China and the 10th Air Force in Burma were essentially tactical air forces although they were using some heavy bombers. The Twentieth Bomber Command, which used B-29's, was originally a completely independent organization, but in the latter part of 1944 it maintained close liaison with Headquarters Army Air Forces India-Burma Theater [AAF-IBT]. Since the theater was under the supreme command of a British officer, the organization of the American and the British RCM units had to be very close. For this purpose, in order to maintain liaison and coordination with the other Allied organizations active in RCM, a committee was established consist-

ing of representatives of AAF-IBT, RAF Air Command South Asia, Royal Navy East Indies Fleet, the Supreme Allied Command of Southeast Asia, and the British Noise Investigation Bureau. Representatives of each of these organizations met monthly at Kandy, Ceylon, for the purpose of establishing theater policies in regard to the use of offensive countermeasures and for exchanging current intelligence information.

Search and Intelligence

Throughout all the India-Burma and China Theaters, the RCM program was exclusively one of search and intelligence. RCM was an insurance against possible effective use by the enemy of its radar weapons. When it became apparent that the enemy's radar was of little value to him, all countermeasures equipment except search gear was put in storage for possible future use.

In June 1944, when the 20th Bomber Command began its operations in Southeast Asia and China, and over the Japanese home island of Kyushu, there was only a limited amount of information available on Japanese radar. Virtually nothing was known of enemy activities in China, whereas a small amount of information had been obtained on the home islands of Japan through coastal searches by Navy submarines. The British Navy and Royal Air Force had conducted fairly extensive RCM reconnaissance in Southeast Asia, but they were handicapped by a lack of adequate DF and measuring equipment. Although it was an established fact that the Japanese possessed a fairly extensive network of EW radars and ground observation posts, their locations were unknown; in addition, little was known of their use of GL or SLC radars. It became apparent early in 1944, with the Allies assuming the offensive in these theaters, and with increased U. S. Air Forces activities, that an extensive RCM reconnaissance program would be essential.

An analysis of the early-warning and air-defense system in China and Kyushu was important to the Twentieth Bomber Command and Fourteenth Air Force in the planning of future missions against possible strong enemy defenses. Likewise, such a requirement existed for the Twentieth Bomber Command and the Tenth Air Force in Burma and Southeast Asia, where such important targets as Rangoon and Singapore were encountered.

The U. S. radar countermeasures program of reconnaissance and analysis in these theaters commenced in June 1944 with the initial strike missions of the India-based B-29's of the Twentieth Bomber Command. For a period of approximately 10 months these aircraft operated in Southeast Asia and China and over the Japanese home islands of Kyushu, providing a great deal of valuable information on enemy radar. Several months after the Twentieth Bomber Command's search program was inaugurated, an interim B-24 Ferret, which was equipped in the theater, was provided to the Fourteenth Air Force for use in China. Initially, this plane was to be used until Ferrets XII and XIII arrived from the United States; however, in November, when the Ferrets did arrive, it was found desirable to operate both the interim Ferret and Ferret XIII in China, leaving Ferret XII available for use in Burma.

The three Ferrets and upwards of a dozen B-29's were equipped with DF antennas and equipment which enabled the location and type of most enemy radars in the theater to be established.

Twentieth Bomber Command. When the Twentieth Bomber Command commenced operations against targets on the Japanese homeland and in Southeast Asia, two significant conditions were met. First, fighter protection could not be afforded the long-range bombers on these missions; and second, operations were conducted against areas which were not accessible to Ferret reconnaissance. In addition, general knowledge and specific data on the characteristics and operational use of enemy radar were very meager. As a consequence, this organization went overseas well equipped with RCM personnel and equipment.

After the initial search work was accomplished, and it was determined that the enemy did not offer a serious threat as far as GL and SLC radar was concerned, the jammers were bench tested and placed in weatherproof storage. Likewise, the supply of Rope and Chaff which had been received by water shipment was

placed in storage for possible future use either by the Twentieth Bomber Command or other Air Force organizations in the theater.

The reconnaissance program was initiated by the search aircraft which had been equipped in the United States. Gradual modifications of this installation took place as new equipment was received and improvements were evolved.

A requirement for the use of DF antennas was foreseen for the purpose of associating given radars with general areas in case jamming later became necessary. Three APA-24's were top-mounted in search aircraft. These were found to be generally unsuitable, both because of DF inaccuracies and because of troubles in the hydraulic drive. A bottom-mounted, retractable modification including electric drive was designed and built in the theater. These proved quite successful in operational use, and about two dozen were eventually installed. RRL later built an electric-drive unit which had to be modified in the field for use in the B-29's.

When it became apparent that the Japanese radar activity was confined to frequencies of 200 mc and lower, plans for the installation of the higher-frequency APA-17 automatic DF antennas were held up. The APR-7 search receiver was used for the monitoring of the 100- to 3,000-mc range, while the APR-5A was kept on hand to cover this band in case enemy activity there required a receiver with higher selectivity.

In addition to the program of radar reconnaissance by the Twentieth Bomber Command, a program for the investigation of Japanese fighter-control communications was initiated in February 1945. Nisei operators (Americans of Japanese ancestry) were flown as combat crew members to monitor enemy fighter and fighter-control frequencies to aid in the analysis of the Japanese use of communications. These communications nets were in general found to be highly inadequate. Prior to the departure of the Twentieth Bomber Command from India, a rather complete analysis of the early-warning net of Sumatra and the Malay Peninsula was carried out.

An evaluation of the overall RCM effort of the Twentieth Bomber Command would indicate that the program of reconnaissance was essentially one of insurance. B-29's gave the Allies the first real picture of the radar situation on Japanese home islands and exploded the theory advanced by some that we could expect much better radar there than in the SWPA. While a few enemy GL and SLC radars were encountered, their effectiveness was never considered great enough to warrant the use of offensive countermeasures by this organization. The lack of Japanese fighter strength and the long distances over which missions were flown eliminated the need for evasive action against the Japanese EW net.

Activities of the Fourteenth Air Force. The need for separate Ferret aircraft in China to augment the search program of the Twentieth Bomber Command was realized in May 1944. This need was based on the fact that the activities of the heavy bomb groups of the Fourteenth Air Force would be confined to different areas than those of the B-29's and would, therefore, require additional reconnaissance.

At this time, there were no Ferrets scheduled for arrival for at least 3 months, so arrangements were made for the construction of an interim Ferret in the theater. A B-24D was furnished by Southeast Asia Command, and the RCM equipment was furnished by the Twentieth Bomber Command. The Ferret was constructed under the technical direction of an RRL technical observer and turned over to the Fourteenth Air Force early in September. Several months later Ferret XIII arrived from the United States.

The Fourteenth Air Force adopted a plan providing a skeleton RCM organization which would have formed the nucleus of a large organization had it become necessary to increase RCM activity. Additional personnel were brought into China so that increased personnel requirements could have been satisfied if the need arose. Small quantities of equipment were procured so that the personnel could become familiar with its operation. A supply of Rope was held in India so that it could be quickly flown over the "Hump" to China if its use became necessary.

The two Ferrets carried out a modest program of reconnaissance operating sporadically for a period of about 4 or 5 months, with the

SECRET

gasoline shortage constantly hampering their activities. By the time that a fairly thorough reconnaissance program was completed in China, it was realized that because of the ineffectiveness of enemy radar there would be little value to continued operations. In May 1945, the interim Ferret was converted to a gasoline tanker and Ferret XIII was transferred to the FEAF in the Philippines, thereby closing the book on Fourteenth Air Force RCM activities in China.

Activities of the Tenth Air Force. Ferret XII arrived in the theater in November 1944 and was attached to the only heavy bomb group of the Tenth Air Force. The Tenth Air Force operated under the jurisdiction of the Headquarters AAF-IBT and confined its operations to strategic bombing and to the aiding of Allied ground forces in Burma until May 1945. Prior to the arrival of this Ferret, RCM reconnaissance had been performed in Burma both by strike aircraft of the 20th Bomber Command and by two RAF Ferrets of Air Command Southeast Asia.

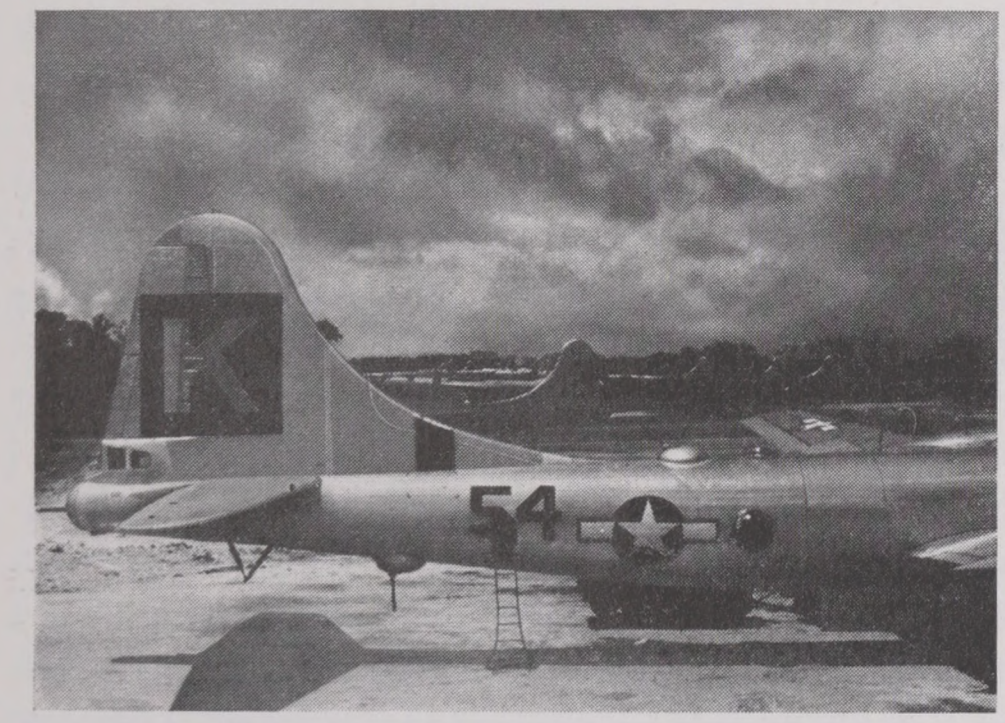


FIGURE 11. Runway and hardstands of North Field, Guam. This field was used by the 314th and 315th Wings of the Twenty-First Bomber Command.

Ferret XII operated in Burma and the Andaman Island chain from November 1944 until April 1945, permitting an accurate accounting of all enemy radar activity during this period. A chain of EW radar stations was encountered along the Burma coast but it was soon discovered that they were not put to intelligent use. On many occasions Allied night-strike formations succeeded in making their bomb runs on targets which were not even partially blacked out. Gun-laying radar was encountered for a period of about 3 weeks in Rangoon just prior to its capture.

With the opening of the Ledo Road and the fall of Rangoon, American commitments in Burma were fulfilled. In May 1945, American Air Force activity in Burma ceased, and Ferret XII was then transferred to the FEAF in the Philippines. The RRL technical observer assisting this aircraft proceeded to the Twentieth Air Force on Guam.

15.6.6 Operational Use of RCM in the Central and Western Pacific

ORGANIZATION

The top theater Air Force organization in the Central and Western Pacific was Headquarters Army Air Forces, Pacific Ocean Areas [AAFPOA], which had under its direct control units of the Seventh Air Force. The AAFPOA organization also acted as Deputy Commander Twentieth Air Force in the Pacific Ocean Area, and as such, DepComAF 20 had control over the Twenty-first Bomber Command of the 20th Air Force. AAFPOA and DepComAF 20 were dissolved in the late spring of 1945, and the organization became United States Army Strategic Air Forces [USASTAF], with command power over the Eighth and Twentieth Air Forces in the Pacific.

The RCM organizations within AAFPOA were under the Director of Intelligence and the Director of Communications. Under the Director of Communications was the Countermeasures Air Analysis Center [CAAC], which was planned as the organization in the theater charged with the job of assembling and analyzing the results of all RCM reconnaissance work done by Army Air Force units. During most of its existence, CAAC maintained close liaison with the RCM analysis organization at CINCPAC (Navy) Headquarters. CAAC undertook analyses of the Japanese air defense system from information derived from airborne and ground-based communication intercepts.

The Director of Communications and CAAC also had control over the Eighth Radio Squadron Mobile, a ground-based communication intercept unit, and Beavers IV and V, ground-based intercept and jamming units. Information derived from these two sources was also used by CAAC in their analysis work. The RCM work done under the Director of Intelligence involved, for the most part, the compilation and publication of radar coverage maps of Japanese-held territories in the Central and Western Pacific Areas.

The RCM organization within the Twenty-first Bomber Command was essentially an operational one, attached to the Communications Section of the Headquarters. No RCM analysis organization existed under the A-2 Section of the bomber command, and, although much of this work was done by personnel in the Communications Section, it was planned to depend upon CAAC for the technical analysis and intelligence functions normally found in Bomber Command A-2.

The five Ferret aircraft assigned to the theater were attached to the Third Photo-Reconnaissance Squadron, a subordinate unit of the Twenty-first Bomber Command. The Ferrets were under Third Photo for administration and maintenance but were under the operational control of the RCM officer of the Twenty-first Bomber Command. In practice, however, the plans for weekly Ferret flights were made at CAAC and passed on to the Ferret flight through the Twenty-first Bomber Command RCM officer. Data gathered by the Ferrets were sent through the Twenty-first Bomber Command to CAAC for analysis and distribution.

Search and Intelligence

By far the most extensive RCM reconnaissance program carried on in this theater was that undertaken by units of the Twenty-first Bomber Command. The bomber command (later Twentieth Air Force) consisted of five wings, and, at first, targets were usually hit by single wings. Consequently, the need was felt for an RCM reconnaissance program which would be complete within each wing. When operations began, neither B-24 nor B-29 Ferret aircraft were available in the theater, and it was necessary to conduct reconnaissance from the strike aircraft themselves. While other aircraft could have done a satisfactory job of plotting EW radars, it was necessary to have the intercept operator fly within the bomber formation in order to obtain the necessary information on GL and SLC radar.

No group was willing to give up too many of its aircraft for RCM search purposes, and since the RCM observers and equipment were also divided equally between the groups in a wing, the reconnaissance job was divided between the four groups in each wing. Each group was expected to provide one observer and RCM-equipped aircraft per mission, giving the possibility of four observers over the target, barring possible mishaps.

The standard RCM reconnaissance equipment was available in various quantities. Some APA-24's were received through Navy Supply Channels, but APA-17 arrived too late to be installed before World War II ended. In order to ensure that one RCM-equipped B-29 per group would be available, two aircraft per bomb squadron, or a total of six aircraft per bomb group, were equipped with Group A parts, including antennas, for all the reconnaissance equipment available. This, in itself, was not a difficult job because racks, power cables, inverters, and r-f cables to the antenna positions were installed in all aircraft in the United States.

Plans were made for the use of the APA-24 DF antenna on the strike B-29's. This was of necessity a compromise because strike aircraft must fly a prescribed course, often not the most desirable from a DF point of view, and navigation in the strike aircraft is seldom as precise as is desirable in Ferreting work. On the other hand, it was necessary to be in the target area when a strike was under way in order to hear any DF gun-laying and searchlight-control radar signals. Although the inherent inaccuracies in DF work using the APA-24 were well known, it was felt that DF on GL signals would give an indication of the area distribution of GL radars in a given target area or in adjacent target areas. Whether this could be done with significant results was never determined. Many cuts on EW radars in the Nanpo Shoto island

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chain and on the southern coast of Japan itself were obtained, and also it was definitely proved that a 70-mc radar, having characteristics similar to the Mark CHI, was being used on ships, probably picket boats.

Actual DF operations by the B-29's were not great. The few APA-24's that were finally built in the theater and the APA-24's received from the Navy did not get into useful operation before the end of World War II. The 58th Bomb Wing arrived on Tinian from India with 12 bottom-mount, electric-drive APA-24's and did the only satisfactory DF work from the B-29's. With the experienced operators available, the 58th Wing turned in some very good locations of EW radars and radar-equipped picket boats. Some little work was done in approximately locating radars by manual left-right switching of symmetrical antennas on the plane, with moderate success. The APA-17 with the 1,000- to 5,000-mc antenna would have been especially valuable in determining whether the 10-cm signals heard were land-based or ship-based, and it is indeed unfortunate that the first unit of this equipment did not reach the theater until two weeks before the end of World War II.

A limited program of airborne communications intercept work was carried on in the Twenty-first Bomber Command. ARR-5 communication receivers and disk recorders (later replaced, in part, by wire recorders) were available in quantity. Lack of ARR-7 until the summer of 1945 necessitated the use of the BC-348 communication receiver for frequencies between 5 and 15 mc. The quality of the recordings made was never good; this was due both to lack of experience on the part of the operators and to equipment limitations, and the program yielded little in the way of usable results.

RCM observers accompanied several single-plane weather strike missions a week and confirmed the fact that there was little EW radar activity and practically no GL/SLC activity on the part of the Japanese when a single plane appeared. RCM reconnaissance was also carried on a number of radar-scope photo missions. All mining missions were accompanied by RCM observers and good success was had in obtaining information on Japanese SLC radar, on which future offensive action was based. RCM observers often accompanied Superdumbos (B-29's used for air-sea rescue work) and navigational B-29's used to lead fighters to Japan, and were able to spend an hour or more in the target area while the strike was going on.

The data collected from all the previously mentioned searches were consolidated at wing level and forwarded to Headquarters, 21st Bomber Command. Because the Countermeasures Air Analysis Center never did have sufficient personnel to handle the job, it was necessary to consolidate the wing reports at bomber command level, analyze the results, and distribute the information to both higher and lower echelons. As CAAC gained personnel, that organization was to take over the analysis and RCM information distribution for the 21st Bomber Command.

The primary job given to the Ferrets was that of mapping the radars in the Nanpo Shoto chain of islands from Iwo Jima to Tokyo Bay. Submarine intercepts and airborne intercepts indicated an extensive EW chain through the Nanpo Shotos and actual locations needed verification. B-29 strikes were usually routed so that they followed the island chain on their trip north. Although this gave long early warning to the Japanese, it was felt that this price could be paid for the great simplification in the navigational problem of the B-29's. However, if the radars could be located by DF, photographed, and then eliminated by bombing and strafing, the navigational advantages of the islands could be used without the disadvantage of added early warning for the Japanese. The pinpointing of the EW radars was the first step in this plan, to be followed by photographs and then radar busting.

The Ferrets, operating from Guam, got their operational training working around Haha Jima and Chichi Jima. Then, staging through Iwo Jima, they worked their way north along the island chain, returning to each island until all radars were accurately pinpointed. Before World War II ended, the Ferrets had succeeded in completely mapping the Nanpo Shoto chain from Haha Jima to Sagami Bay and the photographing phase of the work had begun. The Ferrets also had mapped many of the radars on the southern coast of Honshu by V-J Day.

In addition to their duties as radar Ferrets, communications intercept work was carried on by the four B-24's. The oldest plane, Ferret VI, was stripped of all armament, except flexible tail guns, for night missions, and two radio intercept positions were installed in the nose. The other Ferrets had one radio intercept position installed in the bomb bay RCM compartment. Nisei operators were used for the communications work with good success. The Ferrets operated during the time that a B-29 strike was going on and stayed about 50 miles off the coast of Japan all during the strike. The communications intercept program in the Ferrets was quite successful.

Information gathered by the Ferrets was first consolidated within their own organization,

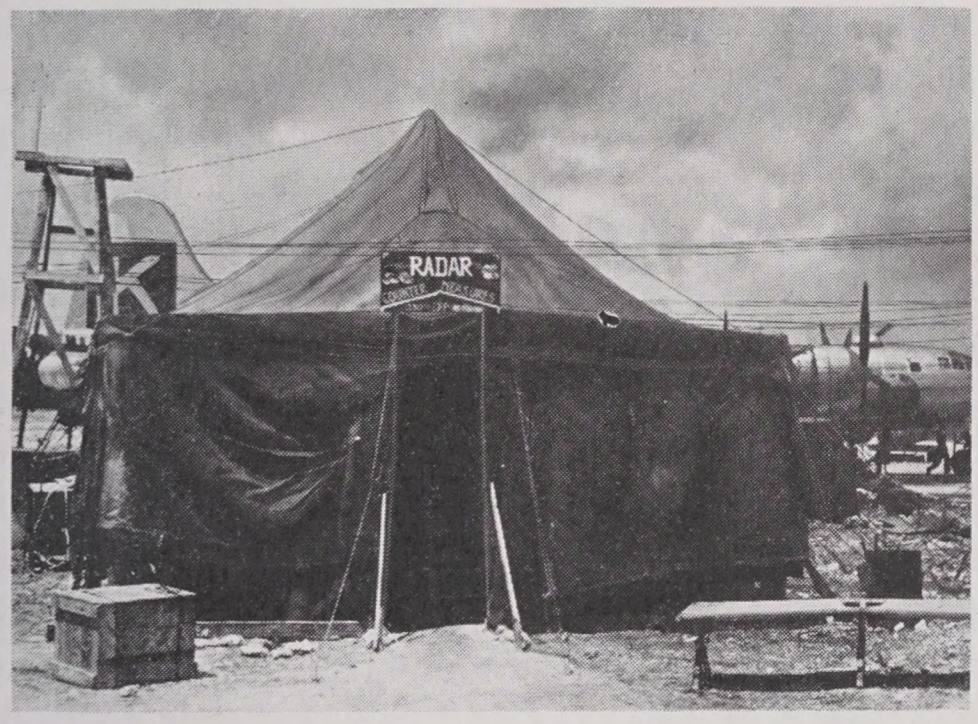


FIGURE 12. RCM shack, 330th Group, 314th Wing, North Field, Guam.

and a special officer, known as an RCM interpreter, was provided for this purpose. The information was then passed through the Twenty-first Bomber Command RCM officer to CAAC, where consolidation of this information with that arriving from other sources was made. The Countermeasures Air Analysis Center put out a weekly summary of Ferret activities and results, and, on the basis of the previous week's results, wrote the directive setting up the Ferret flights for the following week.

Seventh Air Force RCM reconnaissance activities were very limited in scope, both because of lack of personnel and lack of equipment. Three aircraft of the Thirtieth Bomb Group (H) were fitted with Group A parts for the APR-4 receiver and the APA-6 pulse analyzer. The only RCM officer in the Seventh Air Force was the one attached to Air Force Headquarters, and he flew in the RCM-equipped planes of the Thirtieth Bomb Group as intercept operator. The Seventh Air Force, at the time that it was deployed in the Marianas, was flying against Iwo Jima, Haha and Chichi Jima, Truk, and Marcus Island. Most of the EW radars on these islands were logged and the information was forwarded to the organization which preceded CAAC.

EARLY-WARNING COUNTERMEASURES

Aside from the very limited radar-busting activities mentioned in the previous section, the only active countermeasures against EW radar employed in this theater were deceptions. When the 21st Bomber Command commenced operations in the theater, the potential of the Japanese Air Defense system was almost unknown, as were enemy methods of vectoring fighters and enemy zones of air defense. It was believed that diversionary efforts might be successful in reducing fighter opposition at a target, if some of the fighters from the area could be drawn to another target by the diversionary force. The tactics employed were of the simplest kind. A small number of aircraft, usually two or three, were dispatched to the diversionary target and, when they were about 150 miles off the coast of Japan, commenced dropping sufficient quantities of Rope to simulate a force of about 12 B-29's. The evaluation of the effectiveness of these diversionary efforts is extremely difficult; the enemy reaction to the main force was always much greater than the effort against the diversionary force. It should be noted that all of the diversions were flown in daylight. Since the B-29 tactics were constantly changing and different targets were hit on each of these missions, what fighter interception would have been encountered without the diversion is difficut to assess.

The tactical air force of the Tenth Army, based on Okinawa, conducted an RCM diversion over Kyushu in early June of 1945, in support of two photo-reconnaissance Liberators of the Navy VD-1, who were to photograph southern

SECRET

Kyushu. Enemy fighter strength was not completely known, but any fighter opposition at all would make the successful accomplishment of the photo mission almost impossible. Eight P-47's were sent in a diversionary raid to the Sasebo Naval Base in northwestern Kyushu. The diversionary aircraft dispersed Rope on the way to Sasebo to mask the number of aircraft actually present. No enemy fighter aircraft were sighted by the Liberators during the time that they were accomplishing their photographic mission. The diversionary aircraft and some opportunist fighters encountered some enemy fighters near Sasebo and shot down several. As in the previously mentioned diversions, evaluation of the effectiveness of the RCM tactics used is nebulous at best and no definite conclusion as to its success can be drawn.

GL and SLC Countermeasures

Operational Problem. GL/SLC type signals had been intercepted in the Balikpapan area in late 1944 by Fifth Air Force units, but the first confirmed intercept of a 200-mc GL/SLC signal definitely associated with flak bursts made by Twenty-first Bomber Command units was on a mission to Tokyo on January 27, 1945. It is very likely that GL radars were being used against the B-29's during the months of December and January also, but the intercept program did not begin to produce usable information until this mission to Tokyo. The first confirmed intercept of the Mark TA Model 3 occurred during the first week in February 1945 but was not associated with enemy flak.

During the period February through May 1945, there were numerous occasions where continuously pointed fire was observed through undercast. In many cases GL type radar signals were observed, locked on the formation being subjected to the continuously pointed fire. However, blind fire, while obviously radar-controlled, was not consistent in its accuracy, and for the most part was inaccurate. Radar-controlled flak did improve in accuracy as operations continued but never approached German flak in quantity and accuracy.

The major problem encountered by the Twenty-first Bomber Command was that of radar-controlled searchlights. Because of difficulties encountered in daylight high-altitude precision bombing, the Twenty-first Bomber Command commenced low-altitude night missions in early March 1945. The advent of these raids gave the first clear picture of the searchlight defenses available to the Japanese and the tactics employed by them. It was found that at night the Japanese only fired on planes which were illuminated by searchlights; only very rarely were unilluminated planes fired upon. Fighter attacks were only made against those planes which were caught in the searchlight beams. The lack of fighter attacks against unilluminated aircraft indicated lack of satisfactory fighter-vectoring methods and the absence of a usable AI radar in Japanese night fighter aircraft. Thus, radar-controlled searchlights constituted the only menace to night operations.

The first night "fire" raids in March 1945 showed a crude searchlight defense. There were a number of master searchlights, obviously radar-controlled, which were used to direct optically controlled lights on the target. As many as 20 searchlights would carry one plane as it crossed the target area, giving many others a "free ride." As the raids continued through March and April the searchlight tactics improved and, with the aid of the radar-controlled master lights, pairs of lights were used to pass individual aircraft along over the target area, giving the enemy a much better utilization of the searchlights available to him. By May 1945, the searchlight defenses of the enemy were operating very efficiently and posed a serious problem.

Efforts were made to reduce the effectiveness of the searchlight defenses by saturation methods with good success. The bomber stream was compressed as much as possible, so that all of the aircraft passed over the target area in the minimum length of time, with the minimum interval between individual aircraft. The effectiveness of these tactics was evidenced by the fact that the first aircraft over the target area encountered well-organized searchlight tactics, whereas, as the raid progressed and more aircraft came into the target area, the searchlights became disorganized and their previously well-coordinated actions ceased. This is reasonable from the radar point of view. With many air-

craft at altitudes of 5,000-10,000 ft on several axes of attack, all in the target area at once, the operation of the l-f radars used by the Japanese would be seriously hampered by long, minimum-range, permanent echoes at short range and by the wide beamwidths inherent in these radars.

Searchlights also showed themselves to be a problem in the night mining operations of the 313th Wing. The majority of the mining missions carried out by the 313th Wing were to the Inland Sea area, with particular emphasis on keeping the Shimonoseki Straits closed to shipping. The searchlight and flak defenses in this area were quite extensive and the individual mining aircraft operating at altitudes below 5,000 ft were being caused considerable trouble by radar-controlled searchlights.

Studies of reconnaissance information had indicated that the Japanese were employing radars in bands centered at 78 mc and 200 mc for gun-laying and searchlight-control purposes. The 78-mc radar was obviously the Mark TA Model 3, copied from the British GL Mark II. Photo-reconnaissance had shown a number of bowl-shaped depressions alongside heavy gun batteries and their diameter was that which was normally used with the Mark TA Model 3. However, it was never definitely determined whether or not the Mark TA Model 3 was being used for GL only, or for GL and SLC purposes. The picture was less clear at 200 mc. Captured documents had mentioned a number of 200-mc radars which were designed for GL and SLC work, but their intercept characteristics were similar enough to make identification on that basis difficult. It was never definite which of the 200-mc radars were being used for GL and which for SLC.

Of the total number of intercepts of radars having GL/SLC characteristics approximately 55 per cent were in the 200-mc band and 45 per cent were in the 78-mc band. The total frequency spread observed on the Mark TA Model 3 radars was 72-85 mc, with 92 per cent of the signals appearing between 74-80 mc. At 200 mc the total frequency spread observed was 180-220 mc, with 88 per cent of the radars operating between 180-210 mc. The median on pulse length for the 200-mc radar was 5 μsec, and for 78-mc radars was 7 μsec.

Bombing on daylight missions was done in a column of flight squadrons, each consisting of 9 to 11 B-29's. Flight squadrons were usually separated far enough in trail, so that for RCM planning purposes each squadron had to be independently self-shielding against both 78-mc and 200-mc radars. At night, bomb runs were made individually, in a long column of single aircraft, on the same axis of attack, and at the same altitude. Each aircraft had to be protected individually from the previously mentioned radars and could not depend on other strike aircraft for mutual shielding.

Electronic Jammers. The B-29 groups were fortunate compared to the groups in the European and Mediterranean Theaters of Operations, in that they arrived in the theater equipped with Group A installations for all of the standard RCM equipment. There was provided a frame with shock mounts for two A-1D SAR units and four B-1D SAR units. A PE-218 inverter was provided for RCM power, and power cables and connectors came already installed. Antenna ports were provided on every plane, which were satisfactory for search work but not for jamming, and antenna cables were installed. Thus there were facilities provided within the B-29 which made the installation of barrage-jamming equipment a simple matter. A simple field modification of the RCM position gave a satisfactory spot-jamming position. Although all antenna ports provided gave either vertical polarization or cross polarization (when horizontal polarization was required for jamming) with stub antennas, they were a help in getting started.

It appeared most economical at 200 mc to employ barrage jamming in the band 190-210 mc, and to use spot jamming to cover the bands 180-190 mc and 210-220 mc. Calculations indicated that 11 Dina transmitters spaced 2 mc apart would protect 11 B-29's to a minimum range of about 3½ miles against the 200-mc radar most difficult to jam. This required the equivalent of one Dina per aircraft in the flight squadron. High-powered amplifiers for the Dina were on order for use in the event that subsequent tests in the United States showed that more jamming power was needed, and the few

SECRET

received were used on the Dinas set to the center of the frequency band. In some cases Rugs, which would tune down to 200 mc, were used for barrage jamming also. For 180- to 190-mc and 210- to 220-mc spot jamming, an operator was assigned to each of these bands and ordered to jam all GL/SLC signals appearing in his assigned sector. Each spot-jamming operator was supplied with three transmitters, a "setting-on" receiver (APR-4), and a pulse analyzer (later to be replaced by a panoramic adapter). Dinas, modified for spot jamming, were used in most cases but were being replaced by Rugs which had been modified for single-dial operation. The pulse analyzer was necessary to distinguish between EW radars operating on the same frequency as the GL/SLC radars. There were to be Group A installations for spot jamming in six aircraft per bomb squadron, to ensure that each flight squadron would have two spot-jamming installations on everyday missions. This program was never completely carried out during World War II because of a shortage of APR-4 receivers and spot-jamming operators. The RCM observers flew on spot-jamming operations, but their numbers were insufficient to permit the use of two operators per flight squadron. Shortly before the end of the war, the spot-jamming operator training program began to produce a number of men, and the arrival of sufficient quantities of APR-4's permitted a partial realization of the goal of the spot-jamming program.

Because of the smaller band to be jammed, it was decided to use barrage jamming exclusively in the frequency band 72-84 mc and to reserve spot-jamming efforts until frequency spreading on the part of the enemy radar appeared. Calculations showed that seven ARQ-8's, spaced 2 mc apart, would protect 11 B-29's to a minimum range of 1.5 miles against the Mark TA Model 3 radar. This program of barrage jamming at 78 mc was never carried out as planned because of the lack of sufficient quantities of ARQ-8. The usual practice was to set the one or two ARQ-8's available to each bomb squadron to the center of the band 72-84 mc and forego protection over the rest of the band. Often the spot-jamming operators would carry the lone ARQ-8 along with their 200-mc jammers and move it around in the band to cover the greatest possible number of signals. A small number of high-power amplifiers for the ARQ-8 were received, and many more were on order. These were used with the barrage jammers.

The very nature of the formations flown at night made the job of electronic jamming infinitely more difficult than that in daylight operations. Since individual aircraft could not depend upon other aircraft in the bomber stream for protection, no effective jamming could be done from the strike aircraft themselves without carrying an inordinately large number of transmitters in each plane. Consequently the idea of using special aircraft to provide jamming cover for the bomber stream arose. Because each special jamming plane was to carry a large number of jamming transmitters with the corresponding requirement for many antennas on the skin of the ship, the planes became known as Porcupines. One wing, having a more idealistic approach to the problem, called their special jamming aircraft "Guardian Angels."

The wide beamwidths and appreciable side and back lobes inherent in the Japanese 78-mc and 200-mc radars made them susceptible to off-target jamming to a certain extent. Since the requirement would be that of shielding only a single aircraft at a time by this off-target jamming, it was believed that such shielding could be accomplished with the use of reasonable jamming powers. The plan was to equip four aircraft per wing, each with sufficient equipment to jam completely both the 78-mc and 200-mc GL/SLC bands. These aircraft would precede the strike aircraft to the target area and would fly parallel to the bomber stream, at a slightly higher altitude (for air safety purposes), describing a flattened oval between the target and a point outside the target area, with the long axis of the oval parallel to the axis of attack of the strike aircraft. With four Porcupines flying this course in a random fashion among themselves it was felt that there would be a good chance that at least one of them would be in the main lobe of the radar and the other three would be contributing their jamming through the side and back lobes of the radar. On strikes involving more than one wing,

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each wing was expected to contribute four Porcupines.

In order for each Porcupine to jam both 78 and 200 mc it was estimated that each plane would have to carry at least eight 200-mc barrage jammers, five 78-mc barrage jammers, and two spot-jamming operators, one covering 210-220 mc, the other covering 180-190 mc. No immediate plans were made for using spot jamming in the 78-mc band, reliance being placed on barrage jamming. It seemed very likely that it would be necessary to carry amplifiers for the 200-mc jammers, and possibly even for the 78-mc jammers, in order to reduce the minimum jamming range to a safe value.

There were numerous mechanical problems involved in making such an installation in the B-29, particularly those of space, power, and location of antennas. Two different types of installations were being investigated when World War II ended, in an effort to determine the most practical way of installing all of the equipment in the B-29. Use of Rope by the Porcupine will be discussed in the next section of this report.

A Porcupine meeting all of the requirements stated in the previous paragraph was never built before the end of hostilities. Every wing except the 315th Wing (the last wing to begin operation) had four "interim Porcupines" carrying from 6 to 14 transmitters, and these were used on a number of night missions during June and July 1945. As soon as a satisfactory Porcupine, meeting all the operational requirements, was devised, all of the interim Porcupines were to be converted according to this pattern.

With the Porcupines available, the use of electronic jammers in strike aircraft on night missions was of questionable value. However, since equipment was often available, transmitters were installed in strike aircraft for what little protection they might chance to offer.

Jammers were used extensively in mining operations. Mining aircraft were provided with several Dina transmitters and ARQ-8's, when available, set to the center of the band, and, where possible, spot-jamming operators were carried. Assuming that all of the radars "looking at" these aircraft could be jammed by the relatively few transmitters carried, range might be destroyed and some benefit obtained even if the radars could DF on the jamming from the single aircraft. There was some fear that radar plots of the mining aircraft would aid the Japanese in sweeping the mines, and elimination of the range information available from the GL/SLC type radars would force the enemy to depend upon his less accurate EW radars for this data. In one instance when four aircraft were sent to mine Tokyo Harbor at 5,000 ft, they were equipped with jammers, and, in addition, two Superdumbos (B-29's used for air-sea rescue work) orbited the target area carrying spot-jamming operators and dispensing Rope. Searchlights were observed, but not one ever locked on the mining aircraft.

Rope. The physical characteristics of Rope were described in a previous section of this report and mention was made of its response being a function of frequency. A bundle of Rope (three rolls in a sleeve) gave a response at 200 mc which was 0.8 unit (where 1 unit is equal to the echo from a B-17 head on) and a response at 78 mc which was 1.5 units. Preliminary measurements showed that a B-29 had an echoing area of about 1.7 units, consequently, two bundles of Rope would just give sufficient amplitude shielding to a single B-29 at 200 mc. The average pulse lengths at 78 and 200 mc were 7 and 5 μsec respectively, but pulse lengths as short as 2 μsec had been observed, mostly for the 200-mc radars. Thus, all calculations of quantity and dropping rate were made on the basis of shielding at 200 mc and there was more than enough Rope present for shielding at 78 mc. A dropping rate of one bundle of Rope per second was found by calculation to be sufficient to shield a single B-29 at the air speeds employed.

The flight squadron (9-11 B-29's) employed on day missions could all be contained in a single "pulse packet" and the infestation of space with Rope had to be sufficient to shield completely this number of aircraft. The relatively slow rate of fall of Rope ideally would have allowed dispensing from every third flight squadron in the column of squadrons with full protection being afforded, but in practice this was impossible. Assembly and navigation difficulties made it almost impossible to depend

upon any one squadron's being at the point in the bomber stream that was planned for it, and so it was necessary for each squadron to dispense Rope. Each B-29 was to be supplied with enough Rope to dispense at a rate of one bundle per second from the initial point [IP] (or a point closer to the target area if the IP was very far out of GL/SLC radar range) to a point just past the target area. No fighters were available which could carry automatic dispensers and still make the trip to Japan and back, so that the lead squadron had to depend upon electronic jamming for protection.

The wide spacing between individual aircraft in the bomber stream on night missions prevented aircraft from depending upon the Rope dispensed by preceding planes for protection. However, a full complement of Rope was to be carried at night, anyway, because it was felt that an eventual infestation of the target area and approaches would result after the first hundred or so planes had gone over the target, and the confusion value would be great. To improve the infestation at night it was planned to provide the Porcupines with sufficient quantities of Rope to dispense all the time that they were on the upwind leg of their oval course. This Rope would then drift into the path of the bomber stream. About 2,000 bundles of Rope were to be carried by each Porcupine, with provisions for automatic dispensing.

The plans for day and night use of Rope as outlined were never completely carried out. The reasons for this were twofold: first, quantities of Rope sufficient to allow continuous dispensing in the target area were never available; and, second, it was physically difficult to dispense Rope from the B-29. Rope supplies in the Twenty-first Bomber Command never met the demand, and it was not until the first of July 1945 that quantities of Rope approaching 200,000 bundles a month reached the theater. The requirement stated for the Twenty-first Bomber Command was 1.5 million bundles of RR-3/U(T) per month. Because of the scarcity of Rope it was necessary to use the small supplies available in elementary deceptive tactics to "lose" flak and searchlights. B-29 crews were instructed to dispense three bundles of Rope every 10 sec any time that searchlights appeared to be swinging toward them or flak appeared to be "walking" dangerously close. This quantity of Rope dispensed at the rate mentioned would give discreet "pips" on the scope of the Japanese GL/SLC radar. These simple deceptive tactics should not have fooled any radar operator more than one or two times, and yet this method of using the meager supplies of Rope available was successful in many cases for over three months in helping B-29's to elude enemy radar-controlled flak and searchlights. It was obvious that once a plane had been "coned" by a searchlight, no amount of Rope dropping would be effective in helping the plane to elude the searchlight because it was probable that the enemy went over to optical control as soon as an aircraft was coned. This, of course, was borne out by actual experiences. In other cases aircraft which started dispensing Rope when searchlights were seen pointing in opposite directions from the plane, found themselves almost immediately coned. This story was used as an object lesson to crews in an effort to show them the danger of not using their meager Rope supply according to instructions. As Rope supplies increased, these elementary deception tactics gave way to continuous dispensing so that the Rope program was gradually changing toward the continuous dispensing tactics outlined in the previous paragraph.

Dispensing Rope from the B-29 by hand was a difficult task under high-altitude conditions of operation. The pressurized construction of the B-29 made dispensing practically impossible from within the pressurized portions. The most convenient place for dispensing Rope in the B-29 was through the camera hatch in the rear unpressurized section. This method of dispensing was used in the early deception raids at high altitude and was very unsatisfactory. On more than one occasion the crew member dispensing Rope nearly lost his life because of mechanical difficulties with his oxygen hose. At the lower altitudes used in most of the night fire raids, pressurization and oxygen were not a serious problem and dispensing through the camera hatch could be tolerated. Again, however, there was also need for the camera hatch for the purpose for which it was designed, and when cameras for strike photos were carried, dis-

SECRET

pensing between the camera and the edge of the camera hatch was a difficult task. Thus, the need for automatic dispensing equipment in the B-29 was very apparent.

Work on an automatic Rope-dispensing installation was started during February 1945. Through the spring of 1945, several different type installations were attempted with varying degrees of success. It was finally decided that each aircraft should have a maximum capacity of 720 bundles of Rope, and that installation in the rear unpressurized tail section of the B-29 was the best solution. This installation was completed and flight-tested by the end of June 1945, and the Air Depot, Guam, went into production on installation kits. At that time, 400 A-1 dispensers were on hand in the air depot and another 600 were on their way to the theater by air. Prototype installations had been made in one aircraft of each group by the end of July 1945 and the complete installation program should have been well on its way to completion by September 15, 1945. The delay in arriving at a satisfactory installation of the automatic dispenser, with the subsequent delay of the installation program, did not seriously hinder Rope operations in the Twenty-first Bomber Command because adequate supplies of taped Rope, for use with the A-1 stripper, had not yet arrived in the theater by August 1, 1945.

Rope was used quite consistently on all mining missions. For the most part the elementary deception tactics mentioned in the previous paragraph were used simply because of the lack of sufficient supplies of Rope. In a large number of cases they were successful and some of the bogey of low-altitude missions to the well-defended Shimonoseki Straits and Inland Sea areas was dissipated. Rope was sometimes employed by aircraft on weather strike missions which carried RCM observers and by the B-24 Ferrets to stir up radar activity on the part of the Japanese so that more signals could be heard and analyzed during a given mission. Dispensing of Rope usually brought many radars on the air to have a look at the disturbance.

Miscellaneous

Perhaps the most important contribution of the countermeasures war on the ground came in the AJ training phase for radar operators. The most obvious and certainly the first anti-jamming measures to be taken with any type radar set involved the proper training of its operators and a recognition of the various forms of interference and deception to which it might be subjected. On a small scale, organized training activity was carried out in the field prior to mid-1943; before this time a certain amount of AJ instruction had been given in the United States, but this was of a very general nature. With the arrival of substantial quantities of aircraft in the Hawaiian area, late in 1944, the then newly formed headquarters of the Army Air Forces, Pacific Ocean Areas, assisted in a training program already under way in the Hawaiian group as a joint endeavor between the Army Signal Corps and the Navy. The AAFPOA Electronics School, an Army Air Force organization, originally designed to instruct operators of purely countermeasures equipment, found that a great part of its facilities and effort could best be directed toward the training of radar crews in AJ techniques. Accordingly, classes were scheduled for each of the Army units operating in that locality and whenever possible for all similar groups using it as a staging area for shipment to the forward area. In addition to classroom lectures, demonstrations by weekly exercises were held and, with simulated attacks, were executed in close approximation to the Japanese tactics as they were known then. Window and Rope for l-f early warning, as well as microwave searchlight and fire-control equipment, received the greatest emphasis. Electronic jamming and deception were utilized on a somewhat smaller scale. Beyond the value of teaching operators AJ techniques and the operation of countermeasures equipment, these exercises served as a final proving ground for certain tactical doctrines which previously had been no more than suggestions. For each jamming exercise, the battle plan was drawn with special tactical objectives. As the execution proceeded, members of an Army-Navy planning staff were present at the fighter-direction-control boards and the filter centers. Afterwards there would be a critique for each exercise which would attempt

SECRET

to evaluate the success of the mission. This was particularly useful at a time when both Navy and Army Air Forces doctrines for combat use of countermeasures equipment were still being formulated.

Many violations of security on plane-to-plane v-h-f conversations were being observed early in 1945, and at the request of the Commanding General of the 73rd Bomb Wing (21st Bomber Command) the RCM organization within the wing began a program of monitoring and recording Channel C, the plane-to-plane v-h-f frequency. This job fell to the RCM personnel merely because they were the only ones who possessed recording equipment suitable for doing this work. Usually several planes in the wing were equipped with receivers and recorders and continuous records of all v-h-f conversations in the target area were made and the violations of security observed were presented in group and wing critiques. The practice of recording plane-to-plane very high frequency spread to other wings and became common practice throughout the Twenty-first Bomber Command. The program resulted in a marked decrease in security violations over the target area and after an initial several months was continued on a considerably smaller scale. However, even this required too much of the time of the RCM organization, which by this time was busy with the offensive countermeasures program. The responsibility of v-h-f monitoring for security purposes was finally transferred to the radio officer in each group. ANQ-2 disk recorders which were being little used for RCM purposes were supplied by the RCM organization for this work.

An ambitious RCM indoctrination program was set up within the Twenty-first Bomber Command for the main purpose of teaching high-level staff personnel the capabilities and limitations of radar countermeasures. In addition, one phase of the program involved actual offensive operations against U. S. radars in the Marianas chain, mostly for demonstrating to flight crews and staff personnel what the capabilities and limitations of RCM were. This phase of the program lost some of its importance after the use of offensive countermeasures over the Japanese Empire gave the same results.

At the request of Marine Corps units, which operated most of the EW and fire-control radar equipment in the Marianas, B-29's were supplied for Chaff-dropping exercises. Rope and Chaff, supplied mutually by Marine Corps units and Air Force units, were used for practice missions against EW, GL, and SLC radars. RCM officers from the Twenty-first Bomber Command were stationed at the radar sites as observers during these exercises and gained valuable experience in what to expect from their own use of Chaff and Rope. The Twenty-first Bomber Command was assembling a stockpile of S-band Chaff, both for insurance purposes and for training exercises of this type.

Effectiveness of the RCM Program

The evaluation of the effectiveness of an offensive RCM program is a difficult task at best. The tactics employed by the B-29's were fluid and changing continually, and comparison of flak losses before and after the advent of offensive countermeasures was impossible. Attempts to compare flak damage of light squadrons which had poor barrages, because of formation difficulties, with those which had good barrages, gave no significant result. Although no quantitative figure can be stated as being the reduction in flak losses attributable to the use of RCM, it was known from specific instances that the RCM was effective in some cases. A large number of instances of successful searchlight evasions when Rope was employed are on record. These successes achieved for the most part with the elementary deceptive tactics used indicate that the Japanese radar operator was an easy one to fool. As long as the Rope was dispensed before the aircraft was actually coned, the success of this tactic was excellent. Similar evasions of flak through undercast by the use of Rope were reported and, in a number of cases where electronic jamming was employed, searchlights were reported to have searched around wildly, never finding a plane. In a number of instances, spot-jamming operators observed that radars would go off the air when jammed, and "cat and mouse" tactics were often engaged in by the spot-jamming operators and the enemy radars. In some cases, flak would cease or searchlights

SECRET

would be extinguished when the radar signal locked on the aircraft carrying the observer was spot-jammed. On several night strikes in which Porcupines were used, flak officers felt that the lack of serious flak damage was due for the most part to the effect of the offensive RCM on radar-controlled searchlights. The point was reached in some cases where wing operations officers insisted upon the use of Porcupines even though the RCM officer did not feel that they were necessary for the particular mission in question. It can be said that RCM had sold itself to the majority of the operations personnel in the Twenty-first Bomber Command. Thus, an accumulation of evidence of this kind indicates that the offensive RCM effort produced some good results, even though a quantitative statement of flak loss reductions cannot be made.

15.7 RCM IN THE GROUND FORCES

RCM activities by Army ground force units in the Pacific areas were limited in extent. Brief mention of the AJ training activities has been made under the heading "Miscellaneous" in Section 15.6.6 in connection with the activities of the AAFPOA Electronics School. The relatively great distances between Allied-held territory and future Japanese-held targets made ground-based jamming activities, such as those carried on by Beaver III in the Mediterranean, impossible. Three Beaver missions operated during the course of the Pacific war, one in the Aleutians, and the other two in the Western Pacific Area. The major purpose of the three Beaver missions in the Pacific area was that of reconnaissance, and, although they were equipped with jamming equipment, it was never used. It should be pointed out that although Beaver IV and V were Army ground force units, they were under the operational control of AAFPOA.

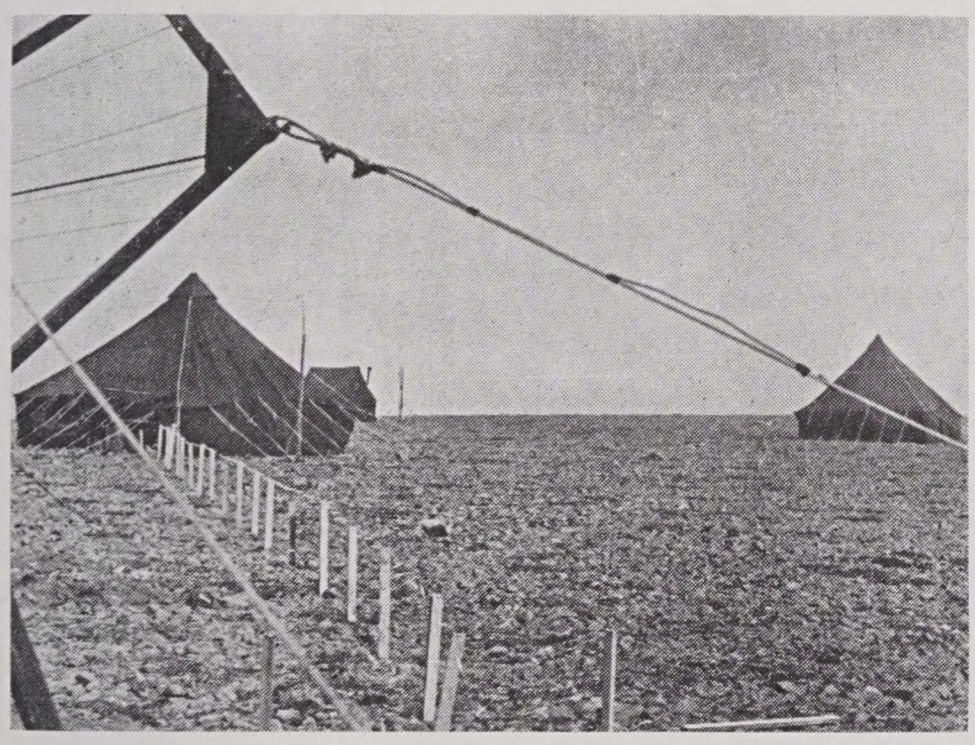


FIGURE 13. Ground-jamming installation (100 mc) for Beaver I mission, Bird Cape, Amchitka.

In August 1943, Beaver I, a platoon of Army Signal Corps personnel, operated a ground-based search position on the island of Amchitka and was prepared, if necessary, to jam the dual early-warning installation on Kiska. Based on the investigations of the first Ferret aircraft in the Aleutians, it was known that two Mark I Model 1, 100-mc, early-warning radar sets were located at an elevation of 525 ft on the shore of Kiska Harbor immediately behind the Japanese main camp area of Kiska. No other radars were found to be operating in the entire Aleutian chain. Since Mark I Model 1 radars had been captured previously at Guadalcanal and Attu, the effectiveness of previously developed jamming equipment against this particular radar was well known and thoroughly successful. It was a fortunate geographical occurrence that the island of Amchitka had a 750-ft plateau on its western tip, 52 miles distant from the enemy radars, almost exactly the limit of a direct transmission path. Technically it appeared possible to deny the Japanese the use of their two early-warning radars by the use of properly sited previously developed jamming equipment, AN/APT-3 plus AM-14/APT.

Upon receipt of a request that facilities be made available for countering the Kiska radars, a platoon of 40 men and 3 officers (part Army, part Navy), known as the First Signal Service Platoon Special, was hurriedly organized and supplied with laboratory prototype equipment from the Radio Research Laboratory and with a civilian technical observer. The unit proceeded to Bird Cape, Amchitka, set up its equipment, and prepared for operations either as a ground-based radar search or jamming installation. With the completion of plans for the invasion of

Kiska, it became apparent that landings should most properly take place on remote portions of the island in a region already blind to the enemy radar. The jamming transmitters could possibly have been used to deceive the enemy by jamming a sector quite far removed from the region of actual assault. On August 4, however, 11 days prior to the landings, it was evident from aerial photographs that the Japanese had voluntarily demolished both radar sets. The mission was completed without the use of jammers by keeping a careful watch to determine that no new enemy radar came into operation.

By the first of 1945, plans for the invasion of Iwo Jima and Okinawa had become definite. The state of the countermeasures war was far advanced by this time and it was realized that offensive countermeasures from the ground-based site would play only a minor role in the Pacific war. Allied knowledge of enemy radar had grown tremendously. Enemy communications, always relatively well known, had begun to increase the knowledge of the tactics and doctrines behind the use of the Japanese radar. Quite strikingly though, knowledge of enemy navigational aids was almost completely absent. The extensive direction-finding nets which the Japanese used to assist their aircraft in land ferry routes were suspected, but actually were known only as vague generalizations. The use of beacons or homing stations or possibly even of a navigational system similar to our own long-range radio-navigation system (Loran) was a complete mystery. Northwest of the Marianas, cutting diagnonally across the Nanpo and Nansei Shoto chains, there was a perpetual weather front which offered navigational problems to the enemy as well as to the Allies. For the purpose of investigating primarily Japanese navigational aids, the First Signal Service Platoon Special was redeployed from Corsica to the Hawaiian Islands where it was put under Army Air Force control and split into two detachments, one destined for Iwo Jima, and the other for the northern tip of Okinawa.

Each detachment was equipped with intercept receivers, and direction-finding antennas for the frequency range 0.5-1,000 mc. Jamming equipment in the frequency range 100-200 mc was also available. By June 1945, search operations were under way which, if continued for a greater period of time, would have shown in all likelihood that the Japanese navigational aids were limited principally to ground-based and airborne direction-finding systems in the 3- to 10-mc range, in addition to a few coded beacons.

Mention should also be made of an Australian Army land-based intercept unit in the Southwest Pacific Area. While its main function was radio intercept, it was on occasion in a position to provide valuable radar data. On December 26-27, 1944, a Japanese naval task force bombarded the Allied Mindoro beachhead. The intercept unit was located nearby, on Ilin Island, and by means of its APR-1 and DF-ing antenna was able to follow the force through all its maneuvers, obtaining invaluable information about the radars used for fire control, air warning, etc.

APPENDIX

RECEIVERS

		PAGE
1.1	Communications Search Receivers	371
1.2	Radar Search Receivers	371
1.3	Radar Early-Warning Receivers	375
1.4	Direction-Finding Receivers	375
1.5	Controlled-Device Receivers	380

TRANSMITTERS

2.1	Communications Jamming Transmitters	381
2.2	Airborne Radar Jamming Transmitters	383
2.3	Ground-Based and Ship-borne Communications Jamming Transmitters	389
2.4	Ground-Based and Ship-borne Radar Jamming Transmitters	390
2.5	Expendable Transmitters	391
2.6	Controlled-Device Jamming Transmitters	392
2.7	Miscellaneous Jamming Transmitter Studies	393

ANTIJAMMING

3.1	Communications Antijamming	395
3.2	Radar Antijamming	403

DECEPTION AND CONFUSION DEVICES

4.1	Mechanical Deception and Confusion Devices	408
4.2	Electrical Deception and Confusion Devices	412

TEST AND TRAINING EQUIPMENT

5.1	Signal Generators	413
5.2	Spectrum Analyzers	415
5.3	Frequency Meters	417
5.4	Miscellaneous Test Equipment	418
5.5	Training Equipment	420

RCM EQUIPMENT

6.1	Electron Tubes	422
6.2	Ultrahigh Frequency Oscillators	425
6.3	Effectiveness of Various Types of Modulation	429
6.4	Antennas	433
6.5	Coaxial Cable, Wave Guides, and Fittings	446
6.6	Noise Sources and Studies	448
6.7	Miscellaneous Research and Development	452

RCM APPLICATIONS

7.1	Airborne RCM Systems	456
7.2	Operational Considerations and Tests	456

1.1 COMMUNICATIONS SEARCH RECEIVERS

895-22 (RP-325) (J. B. Atwood, G. E. Hansell). Describes a method for *identification of pulse communication systems* in enemy use. The necessary equipment consists of a pulse receiver having an adjustable automatic gain control system and low impedance output to either a scope for visual observation of pulse length and type of modulation or to a detector and audio amplifier for aural observation of the average pulse rate as determined by aid of a 5- to 250-kc oscillator. The report includes descriptions of the usual types of pulse communication systems and tells how they can be recognized.

(May 15, 1944)

1045-1 (RP-991) (J. M. Hollywood). Discusses and specifies *changes in SCR-522A to minimize pulse interference* from Freya EW stations, which operate on communication channel frequencies used by Allied fighter aircraft. Nine simple changes in the receiver circuit suffice to enable reception of a ground station until within perhaps 3 miles of a Freya.

(November 16, 1943)

1045-8 (RP-991) (G. P. McCouch). Discusses and specifies *changes in BC-639A to reduce pulse interference* from friendly radars operating near this ground receiver. The chief change is to add a double-triode limiter to clip the pulses to a level permitting speech to be distinguished.

(May 17, 1944)

1045-MR-1 (M. T. Lebenbaum). Describes *modifications of Hallicrafter S-27D* receiver to cover the 17- to 28-mc band. This is accomplished by substituting new coils for those normally used for the 82- to 143-mc band.

(August 2, 1944)

1045-MR-7 (D. K. Reynolds). Describes an experimental model for a *37- to 43-mc panoramic receiver* to display a band of enemy signals on a cathode-ray tube for accurate adjustment of a jamming transmitter. Frequency readings may be read directly to within 100 kc with discrimination of signals separated by as little as 50 kc. The display includes signals down to a level of 10 μv. The frequency to which an associated S-27 receiver is tuned is indicated by a strobe marker on the cathode-ray trace.

(May 16, 1945)

1138-1 (RP-307) (J. I. Heller). Considers the factors which affect the electronic tuning of frequency-modulated *oscillators for panoramic reception.* The purpose is to aid in the design for maximum width and linearity of sweep. Results are tabulated for tests of five oscillators tunable over the 0.86- to 100-mc range, constructional data being given for each.

(March 8, 1944)

1138-2 (RP-307) (J. I. Heller, O. Friedman). Derives formulas for the parameters of *phase networks using reactor tubes.* The formulas are applied to finding the phase network resistor (2,000 ohms) and coil inductance (2.62 μh) for a Type 955 oscillator tube and 6AC7 reactor tube to provide maximum sweep at a center frequency of 23 mc.

(October 23, 1944)

1138-3 (RP-307) (J. I. Heller). Tells of unsuccessful experiments in extending the tuning range by means of *electronic tuning for panoramic reception.* Although reactor tubes will extend the range, they have a low Q in the amplifier stages.

(December 1, 1944)

1.2 RADAR SEARCH RECEIVERS

Airborne Receiver, 40-3,300 mc, 2-mc Output Bandwidth.

Div. 15	RP-144	Army	AN/APR-1
RRL	D-1003	Navy	AN/APR-1

Unit construction superheterodyne with four interchangeable plug-in tuning units to cover frequency range in four bands, an i-f amplifier unit, and a power unit. The receiver is an improved version of SCR-587 (ARC-1), which it is designed to replace. Various tuning units for manual operation and automatic searching with or without sector sweep are described later in this section.

411-TM-73 (D-1901, RP-381) (J. M. Pettit). Modification kit for i-f gain control and AVC switch for SCR-587 and ARC-1.

411-TM-75 (D-1903, RP-381) (J. M. Pettit). Conversion for operation of ARC-1 receiver from a 28-v power source.

411-TM-92 (C. M. Daniell and M. J. White). Airborne antennas for AN/APR-1 (see Section 6.4, M-313 and M-2101).

411-TM-15 (J. M. Pettit). Brief description, parts list, and assembly drawing for variable-range motor drive.

411-148 (D-2600, RP-462) (M. T. Lebenbaum). Modifications of AN/APR-1 to adapt it for use in

setting transmitters for spot-jamming. The changes reduce the bandwidth from 2 mc to about 0.5 mc and reduce the sensitivity of the i-f amplifier by about 20 db. The report includes curves of amplifier response before and after modification.

411-TM-43 (D-514) (J. M. Pettit). Illustrated description of wide-band (9 mc or 0.6 mc) i-f amplifier for AN/APR-4, 40-3,300 mc, choice of bandwidth, otherwise same as AN/APR-1 except for added stage of video amplification.

Type D-101 Tuning Units for AN/APR-1 and SPR-1 Receivers, Frequency Range 75-300 mc, Single-Dial Tuning.

	Manual tuning	Motor drive 28-v, d-c	Motor drive with adjustable sector sweep
RRL	D-101-C	D-101-A	D-101-D
Army	AN/TN-2/APR-1	TU-58B	AN/TN-17/APR-4
Navy	AN/TN-2/APR-1	AN/TN-2A/APR-1	AN/TN-17/APR-4

411-6 (D. B. Sinclair). Operating instructions for type D-101 tuning units.

411-TM-74 (D-1902). Motor-noise filter for TU-57B and TU-58B tuning units for SCR-587.

411-TM-84 (Robert R. Buss). Temporary conversion of TU-57B and TU-58B to sector sweep.

411-TM-141 (F. J. Kamphoefner). Illustrated description and explanation of D-1905 (RP-381) spurious response indicator. The device consists of an externally actuated lever arm to be attached to the hinge end of the tracking cam for the butterfly tuners in the mixer and oscillator circuits inside the tuning unit. The arm detunes the mixer but not the oscillator, thereby enabling true responses to be distinguished from spurious responses due to strong signals. The device may also be used for checking alignment.

Type D-102 Tuning Units for AN/APR-1 and SPR-1 Receivers, Frequency Range 300-1,000 mc, Single-Dial Tuning.

	Manual tuning	Motor drive 28-v, d-c	Motor drive with adjustable sector sweep
RRL	D-102C	D-102a	D-102D
Army	AN/TN-3/APR-1	TU-57B	TN-18/APR-4
Navy	AN/TN-3/APR-1	AN/TN-3A/APR-1	TN-18/APR-4

411-17 (D. B. Sinclair). Operating instructions for Type D-102 tuning units.

411-TM-74 (J. M. Pettit). Tuning units for SCR-587 and motor-noise filter for TU-57B and TU-58B.

411-TM-84 (R. B. Buss). Temporary conversion of TU-57B and TU-58B to sector sweep.

411-TM-141. Already described in this section.

411-16 (D. B. Sinclair). Operating instructions for Type D-104 tuning units for AN/APR-1 and SPR-1 receivers, frequency range 38-95 mc, single-dial tuning.

	Manual tuning	Motor drive 28-v, d-c	Motor drive with adjustable sector sweep
RRL	D-104C	D-104A	D-104D
Army	AN/TN-1/APR-1	TU-56A	AN/TN-16/APR-4
Navy	AN/TN-1/APR-1	AN/TN-1A/APR-1	AN/TN-16/APR-4

Microwave Tuning Unit for AN/APR-1 and SPR-1 Receivers, 1,000-3,100 mc.

Div. 15 RP-212
RRL D-1500

This development of an improved tuning unit for use with D-1003 or D-1005 receivers employs a special short model wide-range oscillator (GL-446 in coaxial line) ganged with a tuned mixer so as to provide single-dial tuning. An adjustable antenna input line permits setting for maximum sensitivity at any one frequency.

411-TM-49 (J. M. Pettit). Preliminary description and specifications for D-1500 including statements as to ease of tuning and freedom from spurious response.

411-11. Detailed description of A-1501 oscillator.

411-TM-85 (P. J. Sutro). Technical information and drawings for A-1503Q oscillator, an improved version of A-1501 as regards simplicity of construction and operation.

Airborne Search Receiver, 1,000-3,100 mc.

Div. 15 RP-135 Army AN/APR-5
RRL A-2600 Navy AN/APR-5

Single-dial superheterodyne whose local oscillator is a GL-446 "lighthouse" tube in a special double coaxial cavity (A-1501, see Section 6.2), and whose mixer is a crystal. The beat frequency, derived from the fundamental frequency of the local oscillator, is fed to a wide-band (10 mc) i-f amplifier centered on 30 mc. The d-c component of the second detector voltage is amplified and observed on a panel meter indicator of unmodulated signals. General characteristics of modulated signals are

SECRET

determined from audio output to headphones. Pulsed signals are analyzed by aid of AN/APA-6 or AN/APA-11 as auxiliary equipment connected to video output. The receiver has a sensitivity of 50μv from a 70-ohm source and the tuning dial accuracy is within ± 1 per cent.

411-40 (R. B. Holt). Detailed description, block and circuit diagrams, and photos.

411-TM-137 (G. E. Hulstede). Suggestion that the frequency range of A-2600 can be extended to 4,500 mc or higher by using harmonics of the beating oscillator. Ambiguities due to harmonic responses can be completely eliminated by switching filters in and out of the antenna leads. The filters would include a low-pass cutting off at about 2,000 mc to eliminate second and third harmonics, and a 2,300- to 4,000-mc band pass to eliminate oscillator fundamental frequencies.

411-143 (Q-1600, RP-286) (W. H. Huggins, J. J. Wedel). Discusses two methods for *blanking AN/APR-5* in order to suppress the interference produced by a local radar system. Both methods require a "trigger" pulse from the radar to actuate an auxiliary blanking circuit. In one method the radar pulse actuates the generation of a well-defined adjustable positive pulse for blanking the cathodes of two r-f amplifier tubes. In the other method the radar pulse actuates the generator of a negative pulse for blanking the suppressor grids. Either method is feasible and only requires an auxiliary circuit to be installed in a small box attached to the receiver. Preliminary tests indicate that suppressor-grid blanking is somewhat preferable and completely effective in eliminating the interference. The report includes circuit diagrams and performance curves.

411-144 (Q-1600, RP-286) (W. H. Huggins, J. W. Kearney). Discusses the theory and practice of using a *pulse stretcher to provide greater audio sensitivity* for a search receiver. The method employs a diode and RC circuit between the video and audio amplifiers to convert a short pulse into a long one which dies away exponentially at a rate determined by RC, for which an optimum value is calculated for a given pulse-repetition frequency [prf]. No more tubes need be added to the receiver. The method, which is that applied in TMR-11T, nearly doubles the audio sensitivity and increases the audio power output due to a pulsed signal by as much as 20 db.

411-152 (R-1000, RP-107) (T. E. Moore, W. G. Wadey). Presents graphs of *characteristics of AN/APR-5A* as measured by methods which are discussed at some length. The chief characteristic shown is the minimum detectable signal, both visual and aural, as a function of frequency for three different mixers. Others include plots of audio output power versus r-f input power at various gain levels, video output voltage versus r-f input power, audio output power versus crystal current, audio-frequency response, and overall gain.

411-230 (W-1500) (J. M. Moran, Geo. Kolstad). Discusses operation and performance of "Silent Knight," a *blanking circuit* that permits a search receiver to listen through an adjacent radar operating in the same frequency band. Laboratory and flight tests demonstrated that SCR-717 signals can thus be eliminated from AN/APR-5 less than 10 ft away. The circuit uses the positive trigger pulse from the SCR-717 modulator to form a delayed pulse. This is applied to the suppressor grids of the first three i-f stages in APR-5 (or APR-4) in order to blank the received radar pulse.

Airborne Search Receiver, 3,000-6,000 mc.

Div. 15	RP-291	Army	AN/APR-6
RRL	A-2700	Navy	AN/APR-6

Differs from airborne search receiver, 1,000-3,100 mc, only in r-f parts. The antenna-mixer assembly is a wave guide; beat frequency is derived from second harmonic of local oscillator.

411-40 (R. B. Holt). Detailed description, block diagram, circuit diagram, and photographs.

411-TM-71 (W. G. Wadey). Information on installation of wave guides.

411-TM-44 (RP-286, R-1800) (R. C. Raymond). A modification of the obsolete SCR-535 identification friend or foe [IFF] set to permit the recording of received signals on a frequency and time chart. The SCR-535 is essentially a transceiver containing two superregenerative receivers which alternately sweep small frequency bands in the 100- and 200-mc regions. The sweeping action is accomplished by rotating condensers driven from a gear train on one end of the dynamotor. The set is modified by (1) substituting a recording mechanism for one of the receivers and its diode rectifier, (2) changing the other receiver to sweep the 550- to 600-mc band, (3) applying the pulse to the recorder instead of retransmitting it. The recorder is mechanically operated by the mechanism previously used to rotate the sweeping condenser.

411-IB-49. Illustrated description and preliminary instructions for installation, adjustment, operation, and maintenance of AN/APR-7, D-2100

SECRET

"Spud" search receiver, 1,000-3,500 mc, with tuned detector and A-2608/A-2612 antennas.

411-IB-49A. Supplementary instructions on D-2105 untuned detector kit to be used with D-2100.

Single Signal Receiver 2,000-4,000 mc and 6,670-10,900 Mc

Div. 15	RP-435
RRL	K-2000, K2100, Q-2100

This partly developed receiving system is designed to reduce or eliminate image and other spurious responses. An image rejection of at least 30 db is accomplished by using three stages of 200-mc i-f amplification. The 2,000- to 4,000-mc range is covered by means of a tuned cavity oscillator (RP-286, Q-1600) using a type 2K28 tube. The 6,670- to 10,900-mc range is covered by a modification of Q-1200 for a 20-mc bandwidth. Preselection is provided by a Q-1900 multiple cavity tunable r-f filter. The system is designed for use with a K-2000 panoramic-presentation unit.

411-259 (S. B. Cohn). Describes and discusses the Q-1900 (RP-442) preselector.

411-268 (Q-1248, RP-286) (H. M. Zeidler, L. Manning, T. E. Moore). Discusses the electrical characteristics of reflex klystron local oscillator to be used in superheterodyne receivers for the 6,600- to 10,700-mc range. The oscillators are coaxial systems using type 2K48 tubes. The tuning device is a resonant noncontacting plunger having low-Q slots to suppress circumferential resonances in the plunger gaps, thus assuring operation free of noise. Initial tests indicate that simple end-point alignment of the oscillator drive and of the reflector-voltage tracking systems will provide satisfactory receiver calibration and operation.

Airborne Recording Unit for D-1005, AN/APR-1, AN/APR-4, or other Search Receiver.

Div. 15	RP-276	Army	AN/APA-23
RRL	D-1800	Navy	AN/APA-23

Unit provides permanent tape record of frequencies and reception times for all received pulsed or other modulated signals. The tape and a marking stylus are driven by a motor which also synchronously drives the receiver's tuning dial through a selected portion of its range. The stylus periodically traverses the width of the tape and makes an electrochemical mark thereon whenever it is actuated by a signal impressed through the video output of the receiver. The tape is likewise marked at 1-min intervals along its length by a timing mechanism actuated by an 8-day clock. Signal frequencies are determined by means of a calibrated scale applied over the tape record.

411-TM-50, 50A, 50B (H. E. Overacker). Detailed description, pictorial drawing, and circuit diagram.

411-173 (W-1300, RP-276) (R. E. Anderson). *Flight tests of the AN/APA-23 recorder* with a companion AN/APR-4 receiver against four radars ranging in frequency from 106 to 567 mc demonstrated that (1) the maximum distance at which signals were recorded for an altitude of 5,000 ft was 70 miles for the SCR-268 and 125 miles for the SCR-271, (2) the maximum response spread was 17 mc against the SCR-648, which is not excessive, and (3) the electrical and mechanical performance of the recorder was entirely satisfactory during all the flight tests. The report gives complete illustrated information about the equipment, test apparatus, and tests.

"Autosearch" Airborne Receiver for Automatically Indicating and Recording Frequencies of Received Signals in the Range from 90 to 1,000 mc.

Div. 15	RP-139	Army	AN/APR-2 (RC-160)
RRL	C-1100	Navy	AN/APR-2 (CXCS)

Indication is by headphones, by a flashing neon bulb behind a slot in the panoramic dial, or by a tape record having correlated time markings. The frequency range is covered in two continually swept bands (90-420 mc and 420-1,000 mc) by two tuned ("butterfly") circuits with separate antennas. The entire frequency range is swept either two or six times per second. The r-f signal voltages are detected by crystals in each circuit and amplified by separate high-gain video channels. The amplifier outputs are commutated to amplifier trigger circuits in proper relationship to give continuous rapid coverage and presentation.

411-13 (E. L. Plotts). The RC-160 receiver (Autosearch).

411-132 (P. A. Pearson). Description of modifications for improving performance of APR-2. These include (1) installation of automatic gain control to prevent excessive spreading of dial and recorded presentation by strong signals, (2) capacitive shunting of lawnmower brushes to eliminate interference from time-marker clicks, and (3) using a fixed voltage divider instead of potentiometer for bias of gas tube, thereby eliminating an unnecessary control.

1.3 RADAR EARLY-WARNING RECEIVERS

Zero Catcher II, 350-700 mc.

Div. 15	RP-287
RRL	R-800

Equipment includes three separate r-f and preamplifier units whose outputs are handled simultaneously by a three-channel a-f unit to operate neon warning lights and/or to provide a warning signal on the interphone circuit. There is also a power-line filter unit to remove ripple and hash from the 28-v d-c supply. Each r-f and preamplifier unit consists of an antenna, low-pass coaxial filter with sharp cutoff at 1,200 mc to prevent interference from 10-cm radar aboard craft, resonant-line r-f tuner, diode or crystal detector, and two-stage a-f amplifier. Two of the units are used for right and left tail warning of German AI and the third for warning of German GL, SLC, or GCI. Their outputs are fed simultaneously to the three-channel a-f unit, two of whose channels operate the warning lights and/or signal and the third is equipped with adjustable time delay to prevent warning by signals from nontracking radars.

411-TM-111 (S. B. Cohn). Briefly describes equipment, explains operating principles with aid of block diagram, and gives specifications.

411-TM-64 (S. B. Cohn). Illustrates and describes structure and characteristics of low-pass coaxial filter in 50-ohm line.

411-52 (S. B. Cohn). Discusses various means for reducing interference from noise and hum in airborne installations of RC-164 Zero Catcher. Hum was reduced by (1) the use of twisted pair shielded cable to carry the signal from the antenna to the receiver, with an isolating transformer at the antenna, (2) ungrounding the input circuit between the isolating transformer and the receiver, and (3) the insertion of an 0.1-h filter choke in series with 28-v d-c supply for the amplifier. Microphonic noise was reduced by substituting crystals for diode detectors, substituting a 9005 diode for the 9004 detector, and mounting the antenna at a point where vibration is at a minimum. Ignition noise was eliminated by bonding and shielding.

1.4 DIRECTION-FINDING RECEIVERS

100-3 (RP-404) (W. E. Rife). Discusses techniques used in *modeling DF loop antennas* and results obtained for a B-24 aircraft in the simulated range of frequencies from 15 to 30 mc. Measurement data are given for calibration curves showing loop bearing versus true bearing, radiation patterns of the rotating loop, and patterns for a loop fixed in various orientations as the aircraft rotates. The tests indicate that operation of DF loops can be satisfactorily predicted by measurement of models.
(June 11, 1945)

"Setter" Airborne Direction-Finding Attachment for Use with D-1003 or D-1005 in Covering Frequency Range from 100 to 750 mc.

Div. 15	RP-298	Army	AN/APA-24
RRL	C-2100E	Navy	AN/APA-24

Equipment covers frequency range by means of four interchangeable r-f heads (C-2110, 100-165 mc; C-2116, 165-275 mc; C-2127, 275-450 mc; and C-2145, 450-750 mc), any one of which is rotated by single antenna mount and drive mechanism and each of which requires a separate balance converter and switch for selecting horizontal or vertical polarization. The device operates on the principle of null signal and requires two bearing observations to eliminate ambiguity as to direction of transmitting station. Accuracy of indication is approximately $\pm$ 5 degrees. Each antenna assembly consists of a horizontal dipole and two vertical dipoles (Adcock) phased so that all four nulls lie on the axis of the horizontal dipole. The assembly is mounted on a driveshaft which is rotated by a hydraulic servo mechanism, remotely controlled. The null is ordinarily detected by headphones; an oscilloscope is used for greater accuracy or to separate two stations differing only in prf rate.

411-TM-61,-61A,-61B,-61C (J. W. Christensen, R. L. Hammett, F. M. Wrightson). Complete description and photographs.

411-156 (W-500, RP-284) (O. W. Whitby). Describes flight tests of a modified APA-24 antenna with electric drive for bottom mounting. The electric drive replaces the original hydraulic drive and the bottom mounting permits the antenna's being retracted against the underside of a B-24. Results showed the superiority of the electric drive, but indicated the need for a better method of controlling the antenna's direction in order to realize more fully the freedom from error that results from bottom mounting. This might be provided by a suggested type of d-c servo system. The report recommends various improvements in the mechanical construction of the antenna and its mount.

411-180 (W-500) (J. J. Wittkopf). Reports performance of modified *AN/APA-24 on B-29 combat missions*. The antenna was bottom-mounted with

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manual retraction and modified for electric drive and interchangeability between aircraft. The report contains photos and drawings of modified equipment as installed and reproductions of 24 DF cuts on horizontally polarized Japanese radar systems operating in the 71- to 211-mc frequency range. Accuracy on the average intercept was found to be nearly comparable to the average navigational accuracy. The operating personnel was well pleased with the equipment.

411-208 (W-1900, RP-298) (J. J. Wittkopf). Describes modifications of AN/APA-42 DF antenna to adapt it for bottom mounting in a B-29 in accordance with recommendations in 411-180 above.

411-TM-61 (J. W. Christensen). Detailed description and operating characteristics of "Setter" Direction Finder.

Div. 15	RP-298	Army	AN/ARD-3
RRL	C-2100	Navy	AN/ARD-3

Same as AN/APA-24 except for antenna heads and balance converters. Made in three models: C-2100A with fixed head (100-165 mc), C-2100B with fixed head and short mounting strut (for use where space is limited) (275-450 mc), and C-2100C with two interchangeable heads (100-165 mc or 275-450 mc).

"Fanny" Homing Attachment.

Div. 15	RP-108	Army	AN/APQ-14
RRL	C-1700	Navy	AN/APQ-14

This device may be used with any receiver and with an antenna system having a null forward and in line with the craft in which it is installed, to enable it to home on a received r-f signal. This is done by maneuvering the craft until the null of the antenna pattern coincides with the direction of the incident signal. Operation depends upon obtaining in headphones an a-f output which is proportional to i-f input. This is obtained by first feeding the receiver's amplified audio output to a diode peak detector circuit having a time constant of ½ sec. The d-c output is then used to change the bias of a 6SJ7 used as a variable-resistance element through which a condenser is charged. The condenser is alternately discharged by a 2050 thyratron. Since the output frequency is a direct function of the value of the charging resistance, it is thus directly proportional to the intensity of the received signal.

411-TMR-10. Gives brief description, including changes made as result of field tests, instructions for installation, schematic diagram, and photos.

411-30 (P. H. Reedy). Discusses principles of operation, including circuit and antenna details, instructions on procedure for installation and operation, and summarizes results of field tests.

411-227 (W-2400) (J. J. Wittkopf). Flight tests of C-1906 indicated generally satisfactory performance as regards accuracy and reliability. The determination of sense was easily accomplished. Great care is necessary in the selection and installation of the two antennas so as to insure physical and electrical symmetry. The report recommends that the audio level be raised to permit simultaneous monitoring of communication channel and homing equipment.

411-198 (J. W. Christensen). Describes and discusses the *C-1906 azimuth homing system* as assembled for use in Navy-type F6F aircraft. The assembly comprises the C-1933 adapter unit, two C-1954 eightball antennas, modified AN/APR-1 receiver, approach indicator, remote-control box, and various mountings. The C-1933 is a revised form of C-1900 with a two-channel r-f and video commutator, pulse-widening and amplifying circuits, AVC and earphone circuits, integrating and bridge circuits, and a power supply. The antennas are mounted on the wings, with the control box and approach (cross-pointer) indicator in the cockpit, and the balance of the equipment in the fuselage. The report discusses the primary uses and limitations of the system as well as the theory and methods of operation.

411-213 (J. W. Christensen). Describes a field measurement method for finding antenna positions and mountings that will yield satisfactory homing patterns with C-1954 (or other C-1950 series) antennas installed in various types of aircraft. Consideration of such factors as frequency range, pattern symmetry, crossover points, fore and aft sensitivity ratios, and balancing of antennas and cables demonstrates that various compromises are necessary to provide good sensitivity and good definition, and to eliminate ambiguous crossover points. Proper procedure is explained in detail.

"Tail" Homing Attachment.

Div. 15	RP-209	Army	AN/APA-48
RRL	C-1900	Navy	AN/APA-48

This attachment used in connection with a suitable receiver and antenna system enables a craft to home in both azimuth and elevation on radar, jamming, or communications signals. The attachment consists of a four-channel r-f switch, a four-channel

commutator, four integrating circuits, and a cross-pointer output meter. The r-f switch successively connects the receiver to each of four antennas, one pair for azimuth and one pair for vertical indication. The video output voltage of the receiver is fed back to the attachment, where it is sychronously commutated and applied to four integrating circuits having long time constants. The switching rate may be adjusted so as not to correspond to the lobe-switching rate of the enemy signal. Indication of right-left and up-down is given by a standard cross-pointer output meter.

411-168 (J. W. Christensen). Discusses antennas and associated equipment used in *v-h-f homing systems*. Results of flight tests show that a satisfactory system for eliminating enemy airborne and ground-based radars and jammers is provided by "sense-homing" with meter indication. The components of such a system, (antennas, lobe-switching receivers and attachments, indicators, and remote-control gear) are illustrated and described, with special emphasis on the design, construction, installation, and measurement of antennas. Flight results are summarized and details are given for a modified system (C-1905) for azimuth homing only.

Airborne Direction Finder, 300-1,000 mc, for Use with D-1003 or D-1005.

Div. 15	RP-298
RRL	M-2300

Equipment represents early developments leading to AN/APA-17, but using oscilloscope with magnetic instead of electrostatic deflection.

411-TM-46 (Arthur Dorne). Preliminary specifications, explaining purpose, listing components, explaining principles of operation, and illustrating installation in plane.

411-134 (Z-800) (J. D. Krays). Tabulates the various antenna spinner assemblies used in the M-2300,-2600,-3000, and -4100 DF systems, and charts the frequency range and application of each type. Sketches are given for the types which have been developed.

411-TM-35 (P. L. Harbury). Illustrated description and explanation of operating principle of all M-4500 spinners. Graphs show standing-wave ratio versus frequency for vertical and horizontal antenna gain of M-4502 dipoles over M-2414 dipole, and polarization discrimination ratios for horizontal and vertical antennas. Photos include typical patterns. These antenna heads extend the frequency range of the M-2300, M-2600, or M-3000 DF systems so as to cover the 1,000- to 5,000-mc band. M-4502 is used with M-2300 and M-2600, M-4503 with M-4100, and M-4504 with M-3000. They are identical except for mounting and relay details. Each consists of two rotational paraboloidal reflectors mounted back to back on a 20-in. disk with a horizontal antenna assembly at the focal point of one reflector and a vertical antenna assembly at the focal point of the other reflector. Between the reflectors is an r-f relay for selecting either one of the radiators. Each antenna consists of a balanced-sleeve dipole with a balun. The antenna pattern consists of a sharp symmetrical single lobe and small minor lobes.

411-287 (E. C. Barkofsky). Describes the M-6600 antenna and drive assembly, discusses the factors influencing its general design and construction, explains the theory of the horn as a radiator and receiver of circularly polarized signals, describes the steps involved in design for a specific frequency range, and presents performance curves. Brief instructions are given for installation, operation, and maintenance.

411-IB-86. Instructs on the operation and maintenance of M-6401 antenna spinner, 135-2,100 mc.

Div. 15	RP-138	Army	AS-108B/APA-17
RRL	M-6401	Navy	AS-108B/APA-17

Designed as a component for M-3000, this spinner consists of a horizontal antenna and a vertical antenna, each supported by a reflecting sheet, mounted back to back with r-f relay between. It covers a wide frequency range with patterns suitable for DF purposes. Except for a new injector box (M-4602), it is interchangeable with M-3001.

Antenna Spinner System, 65-280 mc.

Div. 15	RP-298	Army	AS-222/APA-17
RRL	M-6200	Navy	AS-222/APA-17

This is one of a number of interchangeable spinner systems designed to cover various frequency ranges when used with AN/APA-17 direction-finding equipment for obtaining bidirectional bearings on horizontally polarized signals. The antenna is a rotating double horizontal loop (M-6201) that is selsyn-tuned from a remote tuning unit (M-6202), all operated from an M-6203 power supply through M-6204 cables. The antenna consists of two loops connected in opposition to give an 8-shaped pattern which is bisected through the maxima to obtain the bearing.

411-IB-90. Illustrated description and instructions for installation, adjustment, operation, and maintenance of antenna spinner system.

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411-IB-90A. Correction of minor errors in IB-90 together with supplementary information and photos of patterns, to be used in search procedure with AN/APA-17.

Ship-borne Direction Finder, 300-1,000 mc.

411-109 (J. D. Kraus, H. K. Clark, A. N. Morgan). Description of installation and tests of CXGA on DE-239, using an APR-1 receiver to cover the frequency range. The equipment was found to be an inherently accurate form of direction finder. This broad-band DF system constitutes an adaptation of M-2300 to marine use with AN/SPR-1 receiver. The receiver is fed by a rotating antenna system which is polarized vertically and horizontally. The receiver output operates an oscilloscope indicator (polar coordinate) of received signal strength (radially) versus azimuth of the antenna system. The apex of the pattern on the scope is thus at the bearing of the transmitter.

411-TM-67 (P. L. Harbury). Detailed illustrated description, with block and circuit diagrams and field patterns of homing device, aural or visual.

Div. 15 RP-298
RRL M-3100

This device used with a receiver provides a simple means for homing on an enemy radar system. It consists of two identical stub antennas, with an untuned reflector, an r-f relay, a motor-driven "A-N" cam, a phase inverter stage, and a power supply unit. The relay is connected so as to alternately switch the left-hand and right-hand antenna to the receiver input, being controlled by a microswitch and the "A-N" cam. The rotating cam keys the signal from the left antenna with "A" and from the right antenna with "N" of the Morse code. When the two antennas receive signals of equal strength, the aural indication is a continuous tone in the receiver headphones. A visual indication is provided by aid of the inverter stage and an auxiliary cathode-ray oscilloscope which shows pulses in opposite polarities corresponding to the "A" and "N" indications. When several radars are operating simultaneously with different prf rates on the same frequency, the scope is synchronized to one prf, and "homing" is accomplished by matching the size of the stationary pulses.

DBM Direction Finder, 90-5,000 mc.

Div. 15 RP-271 Navy DBM
RRL M-4100

This ship-borne, broad-band DF system, used with receivers covering its frequency range, provides continuous indication of the arrival direction of radar pulses or continuous-wave [c-w] signals. It also indicates the frequency and polarization of received pulses, which may be further identified by means of an auxiliary pulse analyzer. The DF system consists essentially of two rotating directional antennas and an indicator unit containing a cathode-ray tube whose sweep circuit is synchronized with the rotation of the antenna. The relative bearing of a signal is found by bisecting the antenna pattern on the screen of the cathode-ray tube; this is translated to true bearing by means of a small gyrocompass repeater in the indicator unit. The antenna system consists of either one M-4101 Type E spinner to cover the 200- to 100-mc range or one M-6120 Type M spinner (90-1,400 mc) (Navy-type CFH66137) and one M-4503 Type H spinner (Navy-type CFH66137) to cover the 1,000- to 5,000-mc range. Each spinner is an assembly of a horizontal and vertical dipole and balun mounted with reflectors back to back. The spinners are interchangeable on motor-driven shafts. The electrostatic indicator permits instantaneous DF on sweeping signals and simultaneous DF on several signals.

411-105 (A. W. Alford, W. D. McGuigan, J. Margolin, P. L. Harbury). Report of tests of M-4100 system installed on USS *Gunason,* including discussion of installation problems. Results were generally satisfactory.

411-181 (M-4130, RP-271) (E. C. Barkofsky). Describes *conversion of AN/SPT-6 to a pulsed signal source* to be used for installation calibration of M-4100, and instructs on the installation, operation, and maintenance of the converted transmitter. The changes comprise replacement of the noise modulator by a pulse modulator consisting of a blocking oscillator type of pulse generator producing a 2-μsec signal at a prf of 2,500 per second, rewiring the r-f oscillator to permit shock excitation from the modulator, new bleeder resistors and filter condenser in power-supply section, and new antennas (AS-263/UPT and AS-236/SPT) to cover the 175- to 1,600-mc frequency range. The modified equipment has a peak power output of from 5 to 40 w, depending upon the r-f frequency.

411-190 (W. D. McGuigan, E. C. Barkofsky, J. D. Kraus). Describes the procedure for calibrating DBM-1 shipboard installations, including methods, signal sources, and precalibration checks. The calibration determines the deviations produced by the ship's structure and checks the system's overall alignment.

411-191 (J. D. Kraus, W. D. McGuigan). Describes ship-borne tests of DBM direction finder.

411-233 (J. D. Kraus, H. K. Clark, S. Bera-

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ducci). Describes the performance characteristics of the M-6120 broad-band antenna spinner. The report includes photos of observed antenna patterns over the 80- to 3,000-mc range. There are also curves of bearing deviation and sensitivity, as well as three-dimensional patterns.

411-243 (M-6700, RP-271) (G. Stavis). Discusses the design features of spinner. Its performance is calculated from a theoretical explanation of the horn's operating principle as a radiator and receiver of circularly polarized signals. The text is illustrated with photos, curves, and patterns, and includes an account of how DBM installations can be adapted to use this third antenna. Tests with an airborne radar as the signal course gave signal reception with the aircraft at a distance of 50 miles and an altitude of 1,000 ft.

411-297 (H. K. Clark, W. W. McGuigan, C. A. Mizen). Illustrates and describes the submarine DF system, 2,300-4,600 mc.

Div. 15	RP-303
RRL	M-7100

The equipment consists of a rotating directional antenna and an indicator unit to be used with an auxiliary receiver. The indicator unit is essentially a cathode-ray oscilloscope. The antenna consists of a vertically mounted horn whose mouth points downward to a rotating parabolic reflector making a 45-degree angle with the horn axis. The horn has a circularly polarized response and the system has substantially equal response to vertical and horizontal polarization. The reflector is driven at 200 rpm by a water turbine actuated by a jet from the pump room. The antenna drive is mechanically coupled to the rotor of a two-phase synchro which transmits antenna position data to the cathode-ray tube indicator. The synchro voltage is converted into a quadrature bias to four deflection amplifiers, one for each plate of the cathode-ray tube. Simultaneously the antenna response is fed to the receiver, whose video output is applied to the four amplifiers so as to deflect the narrow pattern in a direction corresponding to a given antenna bearing. The report discusses the reasons for adopting various components, explains calibrating procedure, and gives operating voltage data.

"Moth" Self-Guided Missile to Home on 90- to 520-mc Radar.

Div. 15	RP-188	Army	AN/APQ-14
RRL	C-1600	Navy	AN/APQ-14

411-286 (C-1600, RP-188) (J. W. Christensen). Describes the Moth antennas and chassis developed for use with Glide Bomb, Pelican, and Glomb and describes flight tests in Pelican and Glomb, with graphic presentation of camera records. Experiments with Glomb-Moth gave definite indication of target accuracies on the order of 10-25 ft. Estimates of Pelican-Moth accuracy place the figure at 50-150 ft. The equipment consists of a glider vehicle, carrying explosives, and equipped with an antenna array and a homing receiver. It is released from a large bomber at distances of 5 to 25 miles from the victim radar. The antenna array consists of dipoles which may be rotated to receive either vertically or horizontally polarized signals. The battery-operated superheterodyne receiver is remotely tuned to the exact frequency of the victim radar before the vehicle is released by remote control. The receiver is equipped with lobe switching and furnishes the control voltages to guide the missile. It has a 2-mc bandwidth and a sensitivity of about 50 μv. Several vehicles may be used, as follows:

	Pelican	Dragon	Glomb
Wingspread (ft)	8.4 or 10	12	36
Lb of explosive	500 or 1,000	3,000	2,000-4,000
Support	Carried	Carried	Towed
Type of control	Automatic homing	Automatic homing	Automatic homing, or television and radar homing repeat back with radio control

936-4 (H. H. Buttner). Describes tests to determine feasibility of using *Type-DBA direction finder on B-24J bomber*. The DF equipment consists of a 1.5- to 30-mc superheterodyne receiver, cathode-ray tube bearing indicator, and rotating loop antenna. The results indicate a decrease in accuracy with increase in frequency, fading and distortion at higher frequencies, and a high noise level at all frequencies. The report includes suggestions to overcome operating difficulties.

(January 18, 1945)

1045-12 (J. V. Granger). Describes the design features and constructional characteristics of a ground-based *broad-band DF system* consisting of four antennas to be mounted on a van equipped to detect and analyze radar or jamming signals. The antennas comprise 100- to 300-mc and 300- to 1,000-mc horizontal thick dipoles and vertical Adcocks. The installation includes the mechanism for supporting and rotating the antennas. The report includes standing-wave ratio curves and directional patterns.

(April 23, 1945)

1045-MR-9 (J. W. Keuffel, G. H. Klemm). De-

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scribes a daylight long-range (200-mile) *fighter homing system* (*"Curtain"*) for locating friendly or enemy aircraft or ground transmitters by homing on their 38- to 42-mc transmissions or on navigational aid signals. The equipment designed for installation in a P-51B aircraft is a German ZVG-16 homing unit and FuGe 16Z receiver used with three modified AS-89/ART whip antennas, one for sense and one on each wing to form a grounded Adcock system with figure-8 pattern. The ZVG-16 compares two switched cardioid patterns obtained by switching the Adcock signal 180 degrees in phase and adding the sense antenna signal to give the receiver input. The output is a 27-c sine wave whose amplitude is proportional to the difference of the right and left antenna patterns and whose phase depends upon which pattern has the larger value in the direction of the incoming signal. The course indication is read from an I-101-C left-right meter in a balanced bridge circuit. A signal-strength meter is also provided to give rough indication of the range of the target.

(May 24, 1945)

1045-MR-10 (G. P. McCouch). Describes the *"Judy" instantaneous DF system* operating from vertically polarized 38- to 50-mc modulated or continuous-wave signals. Patterns of a double-Adcock antenna system and associated motor-driven goniometer are presented on a 5-in. cathode-ray tube. The patterns are given by the nulls of the goniometer responses and resemble a two-bladed propeller, being sharper than the indications obtained by presenting the antenna pattern directly. This first model contains no provision for sensing. Ground tests show an accuracy of ± 4 degrees at 40 mc and ± 6 degrees at 50 mc. Satisfactory bearings were taken on an aircraft at 125 miles flying at 15,000 ft with a radiated power of 3-w. The report includes brief instructions for operation and maintenance.

(May 31, 1945)

1045-MR-11 (M. B. Adams, G. H. Klemm). Describes trial installations, in three types of 8th Air Force day fighters, of the British *"Perfectos" system for homing and ranging on German IFF* airborne equipment (FuGe-25A). This system employs a modified version of SCR-729-A beacon interrogator to trigger the FuGe-25A and give range and azimuth data on the responses. The apparatus consists of a pulsed transmitter operating on 125 mc and a 156-mc receiver used with an antenna system whose characteristics are suitable for homing in azimuth. Received responses appear on the indicator scope of GEE navigation equipment. Preliminary operational results are encouraging.

(May 22, 1945)

931-18 (RP-188) (H. Poritsky). Analyzes the *effect of reflected radar waves on the path of a guided missile*. The analysis is based on a theoretical study of the interference field formed by two plane waves and of the equations for equilibrium orientation of an antenna system in that field. The general conclusion is that the missile will home in a wobbly path on a source of continuous radiation. For nonoverlapping pulses the path is more seriously disturbed until the missile gets close enough to be affected by the stronger amplitude of the source.

(August 21, 1945)

1458-2 (RP-445) (H. Busignies, T. H. Clark, H. B. Scarborough). Describes a *spinning loop aircraft direction finder* for guided missile search in 1.5- to 22-mc range. Visual bearing indications with simultaneous monitoring of continuous-wave, interrupted continuous-wave, and keyed continuous-wave signals are provided by a cathode-ray tube indicator and a frequency scanner giving a 50-kc bandwidth on either side of the frequency to which the associated receiver is tuned. Operation consists in the selection of one of three plug-in loops for a desired frequency range, tuning the loop and receiver, and interpreting the cathode-ray tube patterns. The report is essentially an instruction book on the tentative equipment.

(September 29, 1945)

1.5 CONTROLLED-DEVICE RECEIVERS

1305-7 (905, RP-361). Instruction handbook for *magnetic tape recorder AN/SRQ-2* to be operated from a standard receiver in order to monitor, record, or reproduce the control frequencies used in operating guided missiles. This ship-borne model (Serial 4, 5, and 6) gives a 1-min high-fidelity recording, has a response that is constant within 1.5 db from 3 to 53 kc, and the recorded signal has a 35 db signal-to-noise ratio. When used with a S-36 Hallicrafter the 5.25-mc intermediate frequency is heterodyned down to 30 kc in the recording channel.

(April 4, 1945)

1305-9 (905, RP-361). Instruction handbook for *magnetic tape recorder AN/ARQ-12* (Serial 1, 2, and 3). This is a lighter weight airborne model of the equipment described in 1305-7 and gives a 15-sec recording.

(June 5, 1945)

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1305-16 (905, RP-361) (R. A. Isberg, E. W. Adams). Describes the airborne *Peter Pan system of jamming* radio-controlled guided missiles by aid of *magnetic tape recorders* which are described in the report. The system is designed to receive, record, play back, and retransmit enemy control signals in the 40- to 50-mc band. Most of the report is devoted to the theoretical and practical considerations which determine the design of magnetic tape recorders AN/ARQ-12 and AN/SRQ-2, as described in 1305-9 and 1305-7, respectively.

(August 31, 1945)

TRANSMITTERS

2.1 COMMUNICATIONS JAMMING TRANSMITTERS

89-1 (NDRC-58) (M. Cawain). Describes a proposed *communications interference generator,* a modification of a MOPA transmitter circuit, to be used with a narrow-band panoramic search receiver. Interference with voice transmission in the 2- to 20-mc band is provided by an alternate carrier system wherein the carrier frequency is randomly changed by means of code wheels.

(May 1, 1942)

89-2 (NDRC-58). Instruction book for interference generator.

89-3, -4, -5, -6, -7, -8 (NDRC-58). Progress reports from July 1941 to January 1942.

778-2 (NDRC project C-63) (M. E. Campbell). Finds that the *conversion of standard radio equipment to communication jamming* equipment is generally satisfactory. The presence of the transmitter carrier is advantageous and a communications receiver may be used for searching.

(November 11, 1942)

285-1 (C-26) (A. Preisman). Describes the development of an *interference generator* with 50-w output in 15- to 30-mc range. Consideration of all requirements led to the construction of a model consisting essentially of a search receiver with cathode-ray tube presentation and a transmitter modulated with a keyed "warbling" note produced by a multivibrator and thyratron. The report includes results of tests, operating instructions, and recommendations for an improved model.

(June 19, 1942)

285-2 (C-26). Brief description and performance characteristics of *NLS-518 interference generator,* the model described in 285-1.

(February 17, 1942)

285-3 (C-26) (A. Preisman). Discusses the question of barrage versus spot jamming with *interference generator* NLS-518, which is briefly described.

(June 19, 1942)

Low-Frequency Dina—Dinamate, 25-105 mc.

	Div. 15	RRL	Army	Navy
Dina transmitter	RP-267	B-3200	AN/ARQ-8	AN/ARQ-8
Dinamate receiver	RP-250	B-2900		

This transceiver transmits a noise spectrum (150 kc) for spot jamming on the frequency to which its receiver is tuned. The operating principles of the Dina transmitter are explained in Section 2.2 under Dina, 90-220 mc. The equipment comprises a 20-w suppressed-carrier transmitter (using 884 tube as noise source for 150-kc spectrum), a superheterodyne receiver, and a remote-control box. The transmitter's variable-frequency oscillator is the receiver's local oscillator. The circuits are so designed that the set may be pretuned to any desired 5-mc band in the 25- to 105-mc range and then precisely tuned by remote single-dial control of the oscillator frequency. With suitable modifications, including an added 5 mc wide noise source (931 tube) and amplifier for the transmitter, the set may also be used as a barrage jammer.

411-TM-20 (H. Kees). Brief description, block diagram, and photos.

411-TM-68 (O. G. Villard, B. Bacorn). Conversion of equipment for use against German guided missiles.

411-61 (H. Kees, L. Raburn). Field tests with installation in B-24 indicated complete jamming of 15-w amplitude-modulated phone signal at a receiver 2 miles from amplitude-modulated transmitter and 15-20 miles from jammer.

411-223 (B-4900, RP-344) (W. R. Rambo, G. R. Bridgeford). Gives the results of comparative tests on the Radio Research Laboratory [RRL] model of B-4100 and a production model of AM-33/ART, an altered version of the prototype. Because the prototype was found to be superior in power output and bandwidth, various modifications were tested for improving AM-33/ART. These are detailed in the report by means of performance curves. The finally modified unit was thus found to be at least the equivalent of the prototype. Equipment enhances barrage-jamming effectiveness of AN/ARQ-8 in frequency range from 26 to 105 mc with a nominal power rating of 150 w for 4-mc out-

SECRET

put bandwidth. Two HK257B tubes are used in amplifier section and two 836 tubes in the plate power section.

Pad Airborne Transmitter, 21-34 mc.

Div. 15	RP-109	Army	AN/ART-2
BTL	920-11-E	Navy	AN/ART-2

This 50-w barrage jammer is designed for installation on single-seater fighter planes for use against walkie-talkies. The equipment is essentially a superregeneration Dina using a 931 electron multiplier as the source of random noise which is successively amplified by a quenched (blocking) oscillator so as to generate noncoherent (random-phase) pulses having a duration of about 2 μsec and a frequency of about 80,000 per second. The bandwidth is from 0.25 to 0.5 mc.

940-7 (J. C. Schelleng). Preliminary specifications for Pad.

(October 1, 1943)

940-11 (A. E. Kerwien). Brief discussion of theory, particularly as regards action of self-quenched oscillator.

(January 3, 1944)

940-16 (W. J. Albersheim, F. F. Merriam). Shows from laboratory measurements and flight tests that two Pads will jam Japanese walkie-talkies at a much greater distance than will a single Pad. The mid-frequencies of the jammers should be spaced between 250 and 400 kc.

(October 2, 1944)

1179-1. Final report on unsatisfactory production of Pad.

(December 13, 1944)

940-1 (RP-199) (R. C. Shaw). Describes an early type of 50-w *21- to 43-mc Dina jamming transmitter.*

(June 24, 1943)

940-2 (RP-155) (L. G. Young). Discusses the problem of designing an airborne *electromechanical frequency-modulated barrage jammer* providing a 2-mc band of noise with an output of 300-500 w in the 20- to 37-mc range. A proposed method of modulation employs a gas-tube source of noise voltages to actuate a loudspeaker diaphragm. The method was found to be experimentally feasible except that the diaphragm is liable to large amplitude vibrations which cause an arcing breakdown. Any proposed solution of this difficulty requires more complicated alignment and tuning procedures than are needed for electronic systems.

(July 15, 1943)

940-3 (RP-153) (L. G. Young, G. V. Dale). Describes the *conversion of an ATR transmitter to a barrage jammer* employing frequency modulation at audio noise rates. Because the transmitter is intended merely for training purposes, the 21-mc mid-band frequency is not adjustable. The power output is 100 to 200 w respectively from maximum to minimum, frequency modulation adjustable from 0 to ± 1 mc either side of mid-band. The noise source is a 2050 gas tube.

(August 17, 1943)

940-4 (RP-199) (C. R. Burrows). Discusses the theoretical *efficiency of spark transmitters used as jammers.* The basic equipment comprises (1) a rotary spark gap with many randomly separated spark points to generate noncoherent pulses to mask the enemy transmitter, and (2) a band-pass filter to distribute the transmitted energy uniformly over the desired jamming band.

(August 24, 1943)

940-6 (RP-199) (L.E. Hunt). Results of *spark jammer experiments* with type of equipment listed in 940-4 indicate that, for a 6-mc bandwidth, output powers of about 7 w at 60 mc and 80 w at 30 mc should be obtainable for barrage jamming. Narrow bands might be achieved at a considerable sacrifice in power output.

(September 29, 1943)

940-9 (RP-199) (A. E. Kerwien). Finds that the *noise output of 884* gas triode without magnetic field falls off as the frequency is increased from 5 to 30 mc. Use of a magnetic field greatly increases the noise voltage and causes difficulty with firing.

(November 3, 1943)

940-12 (RP-199) (R. J. Kircher, R. W. Friis). Describes two laboratory models for a lightweight 50-w *20- to 40-mc Dina transmitter* which were designed as possible alternatives for the noncoherent pulser used in Pad. Both models use an 884 tube as the noise source.

(January 28, 1944)

940-20 (RP-272) (L. G. Young, N. F. Schlaack, F. F. Merriam, R. W. Friis). Tells of the development and performance tests of *AM-66/AR-XR power amplifier* to be used with AN/ARQ-1 or /ARQ-8 for jamming 15- to 55-mc communications. The equipment gives a mid-band noise output of 500 w.

(February 3, 1945)

940-21 (RP-132, -150, -152, -153, -155, -199, -235, -272, and -356) (M. J. Kelly). Summarizes studies and developments of *barrage jamming of radio communications.* The report outlines research in frequency-modulated jamming produced elec-

tronically, electromechanically, and by ferromagnetic modulation; the use of direct-noise amplification, spark sets, and noncoherent pulses; and various special studies. It tells of the development of AN/ART-1, AM-66/AR-XR, and of electrical circuits designed for Ground Cigar, as well as of the development of expendable jammers.

(February 20, 1945)

966-3 (NDRC-15004) (H. H. Benning). Describes the *conversion of Navy GO-9 to a spot jammer* for the 2.2- to 18-mc range. The 200-w output is largely frequency modulation with noise over a 10-kc band. The noise may be obtained from a microphone in the aircraft engine nacelle or from some other external source.

(March 24, 1943)

966-10 (RP-148) (V. A. Douglas, W. E. Evans). Discusses the *conversion of SCR-808 to a jammer* of communications in 27- to 38.9-mc range. When modulated with random noise it gives satisfactory performance as a readily tuned spot jammer of a-m and f-m receivers.

(November 23, 1943)

966-16 (RP-148) (H. H. Benning, W. E. Evans). Describes the *conversion of GO-9 for spot jamming* in the 2.2- to 18-mc range without impairment of normal operation for c-w communication. An output of about 180 w is largely frequency-modulated, with a 5-kc or 15-kc band of noise from a 2050 gas tube which develops a random noise voltage across the oscillator grid-bias resistor. The report includes schematic diagram and brief operational instructions.

(September 21, 1943)

966-27 (RP-358) (W. C. Babcock, R. L. Robbins, W. H. Tidd, W. R. Young). Recommends a system for *spot-jamming German day fighter communications* in order to prevent coordinated attacks on bomber formations. An idealized plan for each combat wing requires five special planes carrying jam and scan equipment. A simplified system using fewer sets is proposed as a temporary expedient until more sets are available. The report is largely concerned with tactical problems.

(April 27, 1944)

966-29 (RP-148) (V. L. Dzwonczyk). Describes the *conversion of GO-9 for telegraph RCM* in the 300- to 600-kc range provided by the i-f section of the transmitter. An output of about 100 w is obtained for a 3-kc noise band at any desired frequency in the range. The added noise source is a 2051 gas tube placed in the field of a permanent magnet. The report includes schematic diagram, constructional drawings, brief operational instructions, and test data.

(May 23, 1944)

966-36 (RP-150) (W. J. Albersheim, V. A. Douglas, J. W. Emling, W. H. Tidd). Compares the *effectiveness of airborne barrage jammers* of 27- to 42-mc communications. Transmitters under study included AN/ART-3, the AN/ART-7-9 series, AN/ARQ-8, and AN/ART-2. From the standpoint of weight, size, and power requirements AN/ART-3 is found to be the most efficient; it is also the most suitable for jamming German tank communications and GCI communications.

(November 10, 1944)

966-37 (RP-109) (G. J. Heinzelman). Gives results of preliminary tests of *effectiveness of AN/ART-3* high-power Jackal jammer against the SCR-608 and SCR-609 f-m links and the German a-m tank receiver UkwEe. The report extends and corroborates information in 966-32 (Section 3.1).

(October 12, 1944)

966-39 (RP-109) (J. L. Lindner, G. J. Heinzelman). Gives results of *influence of microphones on jamming effectiveness* of Jackal-type noise against FuGe16. The tests indicate that with inexperienced observers an a-m radio link using throat microphones for announcing can be more easily jammed than the same using conventional carbon lip or carbon hand microphones.

(October 3, 1944)

966-48 (RP-272B) (M. E. Campbell, C. R. Eckberg, M. C. Francis). Gives results of flight tests *comparing AM-33 and AM-66* amplifiers with regard to ease of operation and jamming effectiveness against radiophone channels. The AM-66 is found to be more quickly tuned and to have an advantage of 5 db in jamming.

(March 15, 1945)

966-50 (RP-272B) (M. C. Francis). Suggests a *technique for field jamming tests*. Flight time may be minimized by prior assembly and checking of test equipment and prior measurement of radiation pattern and resistance of antennas. The results obtained under controlled conditions are then used to estimate performance on basis of results obtained under test conditions.

(April 20, 1945)

2.2 AIRBORNE RADAR JAMMING TRANSMITTERS

"Mandrel," 85-135 mc.

Div. 15	RP-163	Army	AN/APT-3
RRL	B-2000	Navy	AN/APT-3

[redacted]

Equipment consists of single transmitter-power unit plus remote-control box. The transmitter comprises a master oscillator driving an 829 power amplifier whose grid is amplitude-modulated with amplified power from 931 noise source. It is rated at 10-w output with 2½ w in sidebands having width of 1 to 2 mc, depending on tuning of output circuit. For semibarrage jamming the transmitter is pretuned before take-off. For spot jamming it may be tuned to the desired frequency during flight.

411-35 (C. W. Oliphant). General description, specifications, installation, operation, and maintenance, with photographs and block, circuit, and functional diagrams.

411-TM-19 (E. L. Plotts). Modifications to cover 105-155 mc.

411-TM-19A (R. E. Reid, P. P. Robiano). Energy spectrum.

411-15 (L. E. Raburn). Description, specifications, assembly of components, wiring diagram, test data, and photos of "CXCE," 85-155 mc.

Div. 15	RP-162	Navy	CXCE
RRL	B-1700		

This early type of jammer provided a 15-w c-w output optionally a-m or f-m with 100- and 450-mc sine waves. It used two HY-75 oscillators with one 829 power amplifier and an 829 modulator with 12SJ7 l-f oscillator. As it has been displaced by more effective equipment, no further comment is needed.

"Dina," 90-220 mc.

Div. 15	RP-309	Army	AN/APT-1
RRL	B-2200	Navy	AN/APT-1

Equipment comprises a single transmitter-power unit and (optional) remote-control box. The Dina (*DI*rect-*N*oise *A*mplification) transmits a 5-mc noise spectrum (20 to 8 w) without carrier and is used for either spot or barrage jamming. The transmitter consists of a local oscillator, a 931 noise generator, wide-band preamplifier, mixer, and output amplifier. The oscillator output is fed to the mixer, as is also a selected 5-mc band of amplified noise frequencies. They are heterodyned to produce two widely separated sidebands whose frequency components are equal to the sum and difference of the oscillator frequency and the original noise frequencies. The output amplifier is tuned to either the upper or lower sideband to provide a 5-mc band of noise at the desired output frequency. For barrage jamming the transmitter is tuned before take-off. For spot jamming it is tuned during flight by aid of a search receiver.

411-135 (D. A. Peterson). Reissue of TR-46.

411-135A. See "Rug," 220-550 mc, in this section.

411-TM-59 (R. P. Rabbiano, R. E. Reid). Energy spectrum.

411-TM-110 (L. A. Mayberry). Brief description, explanation of operating principles with block diagram, statement on operation and performance, and specifications.

411-TM-16 (J. R. Caraway). Preliminary specifications and photos of radio-frequency power amplifier, 85-150 mc.

Div. 15	RP-218	Army	AM-14/APT
RRL	B-2800	Navy	AM-14/APT

Tunable wide-band amplifier for B-2200 or B-2000 in frequency range from 85-150 mc. Its power output is from 115 to 140 w with 3-mc bandwidth for B-2200 or 1.5-mc bandwidth for B-2000. HK257B beam power tubes are used to eliminate need for neutralization as amplifier is tuned over frequency range.

411-TM-48 (J. B. Caraway). Tentative specifications of radio-frequency power amplifier, 140-210 mc.

Div. 15	RP-329	Army	AM-18/APT
RRL	B-3400	Navy	AM-18/APT

Tunable wide-band amplifier for B-2200 in frequency range from 140 to 210 mc, rated at 50-w output for 5-mc bandwidth. Eimac 35 TG tubes are used in amplifier section.

"Rug," 220-550 mc.

Div. 15	RP-164	Army	AN/APQ-2A
RRL	F-1500	Navy	AN/APQ-2

Equipment comprises a transmitter unit and a power unit. The transmitter employs a tuned oscillator which is amplitude-modulated with noise from the amplified output of a 931 tube. Tuning is done by varying the position of shorting bars on the grid and plate lines. The power output varies between 20 and 5 w as the frequency is increased, with from 5 to 1.25 w in the 7-mc sidebands. For barrage jamming the transmitter is pretuned before take-off and for spot-jamming the pretuned set can be accurately tuned over a fairly large band during flight by aid of a search receiver.

411-135 (Z-3700). Comparison of the jamming *effectiveness of APQ-2 and APT-1 plus AM-18 at 206 mc* against SCR-268 at Cambridge, Massachusetts, indicated that the Dina-Amplifier combination is about 9 db more effective than the Rug as a spot jammer and slightly more effective than the Rug as a 4-mc barrage jammer.

[redacted]

411-135A (W-400) (J. F. Youngblood, R. E. Anderson). Comparison of the jamming effectiveness of *APQ-2 and APT-1* (with and without AM-18) at 210 mc against SCR-588 at Florosa Field indicated that, for spot jamming, Rug is slightly more effective than Dina alone and 9-10 db less effective than Dina plus AM-18. Rug can be tuned more quickly than the Dina combination when the antenna load is well matched and low in reactance, and less quickly when the load is high in reactance. For 4-mc barrage jamming, AM-18 is 8-17 db more effective than Rug.

411-206 (E. A. Yunker). Describes a simple field modification for operating Rug in the 180- to 200-mc range with an output of 20 w or more. Any 10 mc in this range may be covered with practically no loss in power output by tuning only the plate line. The materials needed to make the change are 2 ft of #14 copper wire and 7 in. of 3/16-in. brass or copper rod.

411-254 (J. L. Clark). Describes a field modification permitting operation of AN/APQ-2 in the range from 147 to 168 mc. This change differs from that described in 411-206 chiefly in the addition of a loading coil in the antenna pickup loop circuit.

"Carpet I," 450-720 mc.

Div. 15	RP-165	Army	APT-2
RRL	F-902	Navy	APT-2

Equipment resembles F-1500 except as to frequency range and addition of small remote-control box. Output varies between 8 and 4 w as frequency increases, with about ¼ total power in 7-mc sidebands. Operational procedure is same as for F-1500.

411-TM-11 (W. D. White). Preliminary specifications.

411-TM-14 (John N. Dyer). Methods for selecting and setting frequency.

411-TM-89 (E. F. Vidro, D. A. Peterson). Preliminary field test report on performance as spot jammer.

411-45 (E. A. Yunker). Detailed description, photos, block and circuit diagrams.

411-117 (E. Barrett). Instructions for modifications (addition of four condensers between ground and the dead ends of the grid and plate lines) to improve performance between 480 and 630 mc. The change eliminates frequency jumps, increases power output, and provides more stable operation. It also provides less critical adjustment for the various oscillator controls, permitting single-dial tuning for spot jamming.

411-150 (E. Barrett, A. Ellis). Specific instructions for single-dial tuning of modified (see 411-117) Carpet I in the 450- to 650-mc range and general instructions for any 60-mc range. The total frequency range is covered in three bands. For each band the antenna coupling control is adjusted for best operation at the highest frequency of the band, and the antenna tuning stub at the lowest frequency, when the transmitter may be tuned solely by plate control.

411-151 (J. F. Youngblood). Reissue of TR-48 with an added tabulation of the frequency allocations relative to the radar frequency for the six Carpets.

"Carpet III," 475-585 mc.

Div. 15	RP-166	Army	AN/APQ-9
RRL	F-2500	Navy	AN/APQ-9

Equipment is a later development than F-902 for covering a small part of the frequency range with greater power (at least 25 w at 475 mc and 15 w at 585 mc). The self-excited oscillator uses two 8012 tubes in push-pull plate circuit amplitude-modulated with amplified output of 931 tube. The transmitter is tuned by means of a front-panel crank which changes the size of a pair of parallel plates in the anode-grid line, thus varying the characteristic impedance. Tuned cathode lines are ganged to the same control. An antenna coupling loop and a coaxial antenna tuner (to minimize reactance) are adjustable by panel knobs. The sideband power is approximately 1 w per megacycle for a 7-mc bandwidth.

411-TM-11 (W. D. White). Preliminary specifications.

411-TM-14 (John N. Dyer). Methods for selecting and setting frequency.

411-TM-96 (R. B. Monroe, R. R. Rhiger). Duplicate of TR-4.

411-62 (J. L. Clark). Detailed description, with block and circuit diagrams.

411-151. Flight tests of the barrage suitability of Carpet III, with and without CHA-28-(3) Window dropped at the rate of 60 units per alternating current per minute, indicated that a 2-mc barrage without Window will shield a tight formation of 12 heavy bombers and that a 2½-mc barrage will shield a loose formation of the same number. Used as a spot jammer, the Carpet III will shield a tight bay of at least 18 heavy bombers, except in the overhead position. The foregoing comments regarding the use of Window with Carpet I also apply to Carpet III.

SECRET

"Air Broadloom III," 150-775 mc.

Div. 15	RP-338	Army	AN/APT-4
RRL	F-3400	Navy	AN/APT-4

This 200-w barrage jammer covers its frequency range by means of two quickly interchangeable split-anode magnetrons, ZP950 (150-390 mc) and ZP579 (350-775 mc), with a single 1,500-gauss permanent magnet. The equipment comprises an oscillator and cooling unit, a high-voltage supply unit, and a modulator and low-voltage supply unit. Frequency is controlled by a single dial which varies the length of a pair of tuning lines and which has a tuning accuracy within ± 3 per cent. Wide-band (5-6 mc) noise modulation is supplied by the amplified output of a 931 tube.

411-TM-114. Salient facts with block diagram, oscillator-modulator circuit, and photographs.

411-108 (W. D. White). From the results of jamming tests conducted against a simulated Wurzburg, it is concluded that the effectiveness of three AN/APT-4 transmitters in covering a 50-mc barrage is equal to or better than that of fifty AN/APT-2 transmitters. Wide bandwidths were obtained by overcoupling the transmitter considerably beyond the point of maximum output. The report includes graphs of spectral distribution for APT-4 at various central frequencies and graphs of relative pulse amplitude for the two transmitters.

411-139 (L. E. Raburn, G. R. Bridgeford). From experiments on the performance of AN/APT-4 it is concluded that the single-dial operation is possible with a power loss of less than 3 db for the 160- to 320-mc range with an AS-114 stub and optimum coupling at 250 mc, and for the 400- to 775-mc range with an AS-115 cone and optimum coupling at 550 mc. Tuning is accomplished by means of the "frequency" control which adjusts the length of the resonant lines. Single-dial spot jamming over a 100-mc range is possible with a loss not much greater than 1 db.

411-204 (W-700, RP-338) (D. F. Wartzok). Describes flight tests to determine the jamming effectiveness of AN/APT-4 with AS-115APT and AS-69APT antennas against a small Wurzburg and a synthetic Giant Wurzburg. From the results of the tests it is estimated that one APT-4 tuned on the radar frequency with optimum coupling and with AS-69APT antenna should shield a composite echo of 50 B-17's at 10,000 ft to within 1 mile from the small Wurzburg or shield 20 to within 1 mile from the Giant Wurzburg.

411-204A (W-700, RP-338) (D. F. Wartzok). Describes flight tests to determine the ratio of the jamming power of one APT-4 to the echo power from one B-17. This ratio, under certain assumed conditions, represents the number of B-17's that the jammer will shield against the radar. The tests were conducted against the SCR-545A. They indicated that one APT-4, tuned to the radar frequency with normal coupling and using a modified AN-148-A antenna, will shield 20 B-17's to a 2½-mile range from the radar site at an altitude of 10,000 ft. Under the same conditions, except for the use of AS-41/APT antenna, only four B-17's would be shielded.

"Carpet IV," 350-1,400 mc.

Div. 15	RP-336	Army	AN/APT-5
RRL	F-3500	Navy	AN/APT-5

This 5- to 25-w spot or semibarrage jammer employs a lighthouse-type triode oscillator which may be tuned from 350 to 1,400 mc in any one of three 300- to 400-mc ranges whose selection requires removal of dust cover. The main tuning control varies the length of a pair of coaxial lines in the cathode-grid and grid-plate circuits, and is supplemented by a trimmer adjustment and oscillator bias control. Dial calibration accuracy is within ± 5 per cent. The noise modulator is of standard type with photoelectric electron multiplier tube as the noise source followed by a wide-band amplifier to provide a 2-mc bandwidth at any point in the frequency range.

411-TM-120. Brief description, block diagram, tube complement.

411-38. Results of experiments with early models of GE L-3 triode as a continuous-wave oscillator in coaxial line tuned circuits. (See Section 3.2.)

411-142 (H. C. Kriegel). Instructions for modifying F-3500 to increase power output by nearly 20 per cent in the 350- to 700-mc range with slightly greater bandwidth. The change involves using electric feedback solely instead of a combined electric and magnetic feedback.

411-196 (W-300, RP-336) (J. F. Youngblood). Describes flight tests of the maximum barrage spacing of AN/APT-5, unmodified and modified in accordance with 411-142, sufficient to screen bomber formations from a small Wurzburg. For formations of 7 heavy bombers at 12,000 ft and of 14 at 20,000 ft in to 75-degree elevation, 2 mc was found to be the maximum spacing for the unmodified equipment and 3 mc for the modified. Further tests indicated that under certain conditions a barrage plus Window combination is less effective than the barrage alone.

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411-TS-7. Tentative specifications of carpet sweeper automatic searching jammer, 480-580 mc.

Div. 15	RP-167	Army	AN/APQ-1
RRL	F-1800	Navy	AN/APQ-1

This airborne transceiver automatically finds a radar signal, locks itself to the frequency thereof, and transmits a jamming signal for a predetermined time interval. Thereafter it either (1) determines whether the signal is still on and, if so, repeats its cycle of operation until the signal disappears, or (2) proceeds to select and jam another signal. The type of operation is preselected by a manual switch. As a receiver, it is tuned by a motor-driven revolving condenser which sweeps through a selected 40-mc band until a signal is detected. The amplified signal voltage discharges a gas tube in a trigger circuit which releases a magnetic latch and actuates a relay to connect (lock) the tubes into the transmitter circuit thus tuned approximately to the frequency of the received signal. While the set is operating as a transmitter, a type 931 tube is energized as a noise source from which the oscillator is modulated to produce the jamming signal. Jamming continues until timing cams close relay contacts through which the gas tube is deionized so that the set can again operate as a receiver.

Frequency-Modulated Spot Jammer, 38-50 mc, and 350-1,000 mc.

Div. 15	RP-203
RRL	A-3500

An experimental l-f equipment supplies a minimum of 60-w useful output modulated either by random noise (100-30,000 c) or by a sawtooth voltage (900-1,100 c, 1,400-1,600 c, or 2,000-4,000 c) to provide a 150-kc frequency-modulation bandwidth at 38 mc or a 250-kc bandwidth at 50 mc (adjustable by panel control). In the oscillator circuit there is a type 829 double beam tetrode push-pull oscillator modulated by a pair of 6C4 reactance tubes, the modulating voltage being the amplified output of an 884, operated either as a noise source or as a sawtooth generator.

411-TM-40 (W. R. Rambo). Explains theory of common-grid type of reactance tube circuit at very high frequency, gives mathematical analysis of Class A operation, and briefly comments on Class B and Class C operation.

411-TM-40A (J. W. Kearney, W. R. Rambo). Indicates behavior of reactance tube circuit at ultrahigh frequency, discusses design of 10-w, 350- to 1,000-mc circuit using type 2C44 lighthouse triode as oscillator with plate and cathode circuits tuned by short-circuited sections of transmission line, and 2C44 triode as reactance tube. The two tubes are installed side by side with grounded grids in a common plane and plates tightly coupled in a common cavity. The phase-splitting network capacitance consists of the plate-cathode interelectrode capacitance of the reactance tube, augmented by electrostatic feedback when necessary. The report includes a circuit diagram, curve of static modulation, and spectrum of energy distribution over a 5-mc band at 775 mc with highly clipped random noise. Parasitic amplitude modulation is kept less than 10 per cent with 1 per cent frequency-modulation bandwidth.

411-82 (W. R. Rambo). Describes Class C operation of reactance tubes, analyzes their use in modulating a 10-w 30-mc oscillator over a 3-mc band, and compares results with measurements from an experimental model.

411-TM-76 (W. R. Rambo). Discusses design of 60-w, 38- to 50-mc model, with circuit diagrams, photos, and curve of frequency shift versus grid voltage.

411-TM-90 (J. W. Kearney). Describes a novel method of producing wide-band frequency modulation by using an electron tube to rapidly switch an additional inductive reactance into the oscillator tank circuit during a fraction of the r-f cycle. The resulting shift in frequency is found to depend upon the length of the switching period and the size of the inductance. The period is the time during which the switching voltage exceeds a certain set value, as determined by the r-f and modulating voltages. The inductance is simulated by transmission lines of proper electrical length. Experimental circuits using a 2C22 or 6C4 switching tube and the same type of oscillator tube with random noise modulation gave 5- to 6-mc bandwidths at 55 mc. Using type 368A and 368AS switching and oscillator tubes gave a 6.5-mc bandwidth at 575 mc. The report includes circuit diagrams and performance curves.

Tunable Magnetron Transmitter, 2,700-3,300 mc.

Div. 15	RP-424	Army	AN/APT-10
RRL	F-5100	Navy	AN/APT-10

This 50-w jammer is designed for use with a modified AN/APR-5 receiver for searching and monitoring, a D-2200 panoramic analyzer to aid in setting the transmitter to the correct frequency, and accessory equipment to provide a complete spot-jamming system. The transmitter covers the frequency range by means of four interchangeable single-dial oscillator plug-in units using four different magnetrons to cover the entire frequency range. The noise source is a 6D4 gas tube giving a

SECRET

frequency response from 100 kc to 3.5 mc. Tuning is accomplished by mechanically changing the resonance characteristics of the magnetron's internal cavity. A line stretcher is also provided in the antenna line to prevent "moding." The antenna system includes one M-4902 with crystal probe and two AS/125 antennas.

411-187 (W-1600, RP-454) (J. M. Moran). Describes flight tests in three B-17 installations of AN/APQ-20, consisting of AN/APT-10 transmitter, AN/APR-5A receiver with panoramic presentation, and associated equipment. The operator, after setting the jammer on the frequency of a radar which he has located, simultaneously monitors the radar and jamming signals by means of a look-through arrangement. Jamming APG-1 was found to provide adequate screening above 8,000 ft and a look-through range of 3-4 miles, whereas screening against SCR-545 was found to be adequate above 25,000 ft, with a look-through range of 10 miles.

411-187A (W-1600, RP-454) (J. M. Moran). Describes two preliminary flight tests of AN/APQ-20 system installed in a B-29. Screening against APG-1 was found to be adequate when approaching at 8,000 ft or higher, and inadequate after passing overhead at 15,000 ft or less; the look-through range was about 6 miles at 15,000 ft. The system is inadequate against SCR-545 below 25,000 ft; the look-through range is greater than 25 miles at 25,000 ft.

411-265 (W. D. White, J. L. Clark). Briefly describes the AN/APQ-20 spot-jamming system consisting of the F-5100 transmitter, AN/APR-10 receiver, D-2200 panoramic adaptor, and antennas M-4902 and M-6807.

IB-76. Description and instructions for installation, operation, and maintenance of F-4800 transmitters.

411-296 (W. R. Rambo). Describes the design installation and operation of an interim prototype of AN/APQ-21 and discusses receiver and antenna requirements for an ultimate system. This noise amplitude-modulated transmitter employs a single lighthouse ZP-572 (2C38) tube as oscillator and a 6D4 noise source. It has an output of 10-35 w and an average bandwidth of 2 mc. By adjusting three panel controls, the oscillator frequency may be varied from 1,000 mc to 1,925 mc or from 1,700 mc to 2,500 mc; changing from one range to the other requires slight changes in the oscillator. The 300- to 1,000-mc range is covered by means of an l-f feedback assembly. The transmitter may be used with M-2101 antenna.

411-266 (W. D. White, J. L. Clark). Describes the AN/APQ-27 remote-controlled spot-jamming system consisting of the F-5150 transmitter, AN/APR-10 receiver, D-2200 panoramic adaptor, and antennas M-6807 and M-4902. The frequency band is covered by means of six plug-in tuners, motor-driven and controlled from a box at the operator's position. The magnetron oscillator should be installed near the antenna. A 6D4 tube is the source of a 3-mc noise band from a modulator-power supply unit installed at any relatively accessible location. In the control box is a power input switch, plate voltage pushbuttons, tuning switch, meter for antenna indication, and selsyn frequency indicator from the tuning mechanism.

411-295 (J. G. Stephenson, M. B. Adams). Describes preliminary experimental work on single-dial jammer, 60-300 mc.

Div. 15	RP-346
RRL	F-6300

This proposed 20- to 50-w spot jammer with push-pull oscillator circuit has single-dial tuning that is accomplished by aid of a spiral construction of the tank inductance. Maximum output bandwidth is obtained by using a small shunt capacitance in the tank circuit, simultaneous grid modulation, and a balun type of output coupler. Type 3C24 tubes are used in the oscillator and a 6D4 is the noise source.

411-TMR-112. Brief description, specifications, photos of experimental model, parts list, and construction drawings.

411-TM-129 (H. E. Overacker). Brief description, block and circuit diagrams, specifications and details of operating procedure of "Automat" search and lock-on jamming system, 40-1,000 mc.

Div. 15	RP-380	Army	AN/APA-27
RRL	U-600	Navy	AN/APA-27

This control device automatically sets a jammer on the frequency to which a standard search receiver (30 mc intermediate frequency with single-dial tuning) is tuned. It sweeps the receiver over a selected frequency range, stops the receiver when a signal is received, sweeps a standard jamming transmitter over the same frequency range, and stops sweeping the jammer when it is tuned to the receiver frequency. The device provides for all required types of search and lock-on jamming. The Automat circuits are operated by intermediate frequency taken from the receiver Panoramoscope output plug. The intermediate frequency is fed through a high-pass filter into a converter tube where it beats with the output of a 30-mc oscillator

to provide video frequencies. These are amplified, fed to a sharpening circuit, and applied to a trigger circuit whose rectified output operates relays connected to small motor-drive units attached to the front panels of the receiver and transmitter. The receiver and transmitter are fed by separate antennas, that to the receiver being disconnected when the jammer is on, receiver pickup then being accomplished through a small separate antenna.

653-1 (127, RP-136) (P. C. Goldmark). Describes the development of *Pimpernel automatic jamming system* for the 450- to 590-mc range. This airborne equipment consists of a receiver, which automatically sweeps any 20- to 50-mc manually selected band in the frequency range, and means for controlling any associated jamming transmitter. Receipt of a radar signal stops the receiver sweep at the signal's frequency, starts the jammer, and tunes it to that frequency, and either continues interrupted jamming at adjustable intervals or ceases jamming and starts new search, as determined by panel switch. The report contains photos and constructional drawings of model.

(June 2, 1943)

1045-3 (BB700, RP-165) (J. T. Wilner). Describes *modifications of Carpet I permitting 335- to 415-mc operation,* using the existing RC-156-A antenna. The principal changes involve adding condensers to change the resonant frequency of the oscillator plate and grid circuits, extending the antenna tuning head, and substituting a new pickup loop.

(January 20, 1944)

2.3 GROUND-BASED AND SHIP-BORNE COMMUNICATIONS JAMMING TRANSMITTERS

Cigar 15-Kw Jammer, 38-52 mc.

Div. 15	RP-356	Army	AN/MRT-1
West	1309, 1310	Navy	AN/MRT-1

This readily transportable equipment is carried in two HO-27 shelters for the oscillator and power-supply units. The oscillator is a self-excited WL889R tube with tunable grid and cathode Lecher lines. Mechanical noise modulation having a 3.5-mc frequency range at 38 mc and 7-mc range at 54 mc is developed by an inductor loop rotated between the grid lines. Power is supplied from a three-phase source by means of a transformer and six-phase mercury-vapor rectifier. The antenna is a three-mast, vertical rhombic.

1309 and 1310-1 (J. T. Thwaites). Brief illustrated description of 38- to 52-mc equipment and 18- to 70-mc modification for countermeasures against guided missiles.

(April 14, 1945)

1107-1 and 1107-2 (RP-197) (R. M. Baker, B. Cassen, and D. Bartlett). Describe the development, construction, and installation of two special resonant-line type f-m oscillators for the Cigar project.

(April 10, 1944 and June 11, 1944)

940-17 (RP-356) (J. P. Schafer, L. E. Hunt). Describes the construction and installation of a three-section low-pass filter for suppressing Cigar harmonics in the 100- to 150-mc band. Tests indicate a 64-mc cutoff and a reduction of at least 35 db for the unwanted band.

(October 16, 1944)

940-18 (RP-356) (P. J. Schafer). Illustrates and describes a circuit providing a-f grid modulation of Cigar 15-kw output for 100- to 15,000-c operation, with no circuit adjustment other than the change of input frequency.

(October 16, 1944)

940-19 (RP-356) (J. P. Schafer, L. E. Hunt, G. V. Dale). Reports results of investigating means for modulating Cigar with random noise. Tests of a self-blocking superregenerative circuit controlled by circuit noise indicate a smaller power output than could be obtained from a system employing grid-bias modulation. The latter method was adopted and developed to provide a 500-kc noise band at 40 mc with 12-kw output. Noise from a 6D4 gas tube amplified by five stages was the source of modulations. Investigations were not carried beyond the exploratory stage because of lack of interest in improving Cigar's jamming effectiveness.

(October 17, 1944)

1045-10 (BC200, BD301, RP-995). Describes a proposed *modification of Ground Cigar for spot jamming* the 38.5- to 42.3-mc radio link of the German fighter-control system, which is also briefly described. The changes require rebuilding this 600-w barrage jammer so as to provide spot jamming with noise from a gas tube and increasing the height of the antenna by some 300 ft. From test results it is concluded that a Britain-based new installation would provide a useful jamming signal in the Holland-Ruhr region instead of merely along the English coast.

(July 20, 1944)

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2.4 GROUND-BASED AND SHIP-BORNE RADAR JAMMING TRANSMITTERS

"Tuba," 480-500 mc.

Div. 15	RP-100	Army	AN/MPQ-1,
RRL	A-500		SC 94.14

This high-power barrage jammer is installed in and operated from nine trucks with two trailers. It comprises two 25-kw transmitters each using a resnatron tube separately noise-modulated over half the frequency range. The corresponding antennas are rotatable paraboloids horn-fed from a wave guide. Power is supplied from three 75-kw diesel-electric generators.

411-TM-7 (W. W. Salisbury). Preliminary specifications and discussion of possible applications on frequencies between 100 and 3,000 mc for ground-based, ship-borne, and airborne installations, including drawings of Sloan-Marshall resnatron tube and block diagrams for various types of installation.

411-88 (W. G. Dow, J. Galt). Derives an equation for computing the radar-to-jammer distances at which a high-power ground-based transmitter is effective in jamming a German AI radar operating in the 470- to 490-mc range. Assumed operating conditions include four types of jammer spectra and various positions of target with respect to radar and jammer. The results of computations are shown by a number of curves in which the distance is plotted as a function of the difference between the frequency to which the receiver is tuned and the mid-band frequency spectrum of the jammer. These curves facilitate choice of the most effective type of jammer spectrum. General conclusions are that jamming is much more effective when the radar is pointed toward the jammer, and that the maximum distance for effectiveness increases rapidly with decrease in radar-to-target range.

411-155 (W-800, RP-100) (D. A. Peterson). Concludes from described measurements on the ground and in the air that Tuba's field intensity at 25,000-ft altitude is sufficient to jam completely the German Fuge 202 radar, head on, at a distance of 200 miles and including a 32-degree arc. At 518 mc the horizontal beamwidth is 32 degrees (110-mile arc 200 miles from Tuba) and the vertical beamwidth is 5.2 degrees, with the maximum lobe directed 3.2 degrees above the horizon. The effective jamming range is primarily limited by the radar horizon, rather than by the power radiated. For one adjustment the bandwidth is about 2 mc, limiting the equipment to spot jamming. The antenna has a power gain of 248 over an isotropic radiator.

411-222 (W. Salisbury, E. S. Welch, J. Livingood). This comprehensive and profusely illustrated report presents the technical details involved in the successful design, construction, installation, and operation of three complete units supplied to the British to protect bombers from German night fighter radars. Each unit contained two transmitters with nominal 25-w rating and actual power output depending upon operating conditions and requirements. The transmitters were built around resnatron tube (see 411-70 and 411-126, Section 6.2) oscillators. The tubes for the first unit were tunable from about 480 to 510 mc, for the second unit from 340 to 520 mc, and for the third unit from 460 to 625 mc. Amplitude modulation of the oscillator control grid with either noise or sine wave provided a jamming bandwidth of 2-4 mc, the wider bandwidth being associated with a smaller per cent modulation. The first unit functioned effectively during the summer of 1944 until the Germans abandoned the 490-mc band. Because of the favorable course of World War II the other two units were not used against the enemy. Tests indicated they would completely jam the Fuge-202 down to 0.2 mile between the radar and the target when the radar is approaching Tuba at an altitude of 25,000 ft, and at all distances up to 200 miles within a 32-degree arc. These conclusions assume 14-kw output within 1 mc of the radar frequency.

Elephant System, 2,000-4,000 mc.

Div. 15	RP-457
RRL	S-9000

This ship-borne system incorporates 1-kw transmitting equipment to generate and radiate a noise-modulated r-f jamming signal in the 2,460- to 3,610-mc range and receiving equipment to intercept enemy radar signals in the 2,000- to 4,000-mc range and to present visual information comparing the received and transmitted signals.

Operation of the system is centralized at the receiver console housing two receivers, either of which may be used with secret antennas, to search for enemy radar signals, or with a DF antenna and DBM-1 direction finder, to obtain compass bearings on the source of a signal. When a search receiver intercepts a signal which is to be jammed, the receiver is connected to an antenna for monitoring the jamming operation. Meanwhile the other receiver may continue to search. End receiver uses a 2K-48 reflex klystron in a tunable coaxial cavity as a local oscillator. Each has a unit for presenting the spectrum of a received signal. The output spectrum from the monitor receiver is also switched to a

Panoramic scope in the transmitter console for comparison with the picked-up jamming signal.

The transmitter uses a ZP-599 magnetron oscillator modulated with noise from a 6D4 source. A transmitting antenna is located at each end of the ship. The proper antenna is automatically selected and kept trained on a specified bearing by means of a system of servo amplifiers operating in conjunction with the ship's gyro on-course system. The antenna system includes one for monitoring purposes and a dummy to absorb power when a jamming signal is not being transmitted.

The system was intended to be used with various receivers and transmitters so as to cover a wide range of frequencies of which only the 2,000- to 4,000-mc range was actually developed, as detailed in the accompanying list of reports.

411-IB-51. Preliminary instructions for Elephant.

411-220 (C-9000, RP-462) (C. C. Loomis). Explains the considerations upon which are based the design of the *radar video analyzer.* This is an electronic unit which accepts the video output of a search receiver and presents it as readings on two meters which indicate the pulse width and prf of the received signal. The pulse amplitude may vary from 0.4 to 2.6 v, the width from 0.5 to 25 μsec, and the repetition rate from 30 to 5,000 c. The unit operates on negative pulses from the search receiver. The analyzer identifies and reidentifies a particular radar indicated by a search receiver, assuming that the video characteristics are unchanged.

411-270 (F-9000, RP-461) (W. R. Rambo). Describes and discusses the salient design features of the initial laboratory model for the 90- to 250-mc transmitter. Preliminary performance curves indicate satisfactory power output, modulated bandwidth, and efficiency.

411-275 (S-9000, RP-457) (J. F. Byrne, J. M. Pettit). Final report on RRL development of Elephant system.

2.5 EXPENDABLE TRANSMITTERS

411-59 (G-700) (E. Fubini, T. S. Kuhn). Calculates the practicability of expendable jammers. It is concluded that such an equipment is useful in raids against isolated GCI or GL systems whose location and frequency are accurately known. The weight and volume become too great if these factors are not known. The equipment could also be used against EW, but is not useful against AI or in screening boats, except for high-speed boats.

Dina Chick Jammer 1 to 7 mc.

Div. 15	RP-132	Army	SC-95.04
BTL		Navy	NS-200

Ten or more of these parachute devices are launched from the bomb racks of moving planes in order to jam c-w telegraph and telephone circuits within perhaps 1 mile from the place of landing. Each unit radiates about 1 w over a specified 500-kc band to which it is tuned in the 1- to 7-mc range. It operates from dry batteries for about 4 hr after a clock-determined starting time. The final model employed a 6D4 tube as the noise source with a three-stage amplifier and was housed in a cylindrical container of about the size and shape of a 100-lb bomb. A 100- to 150-ft trailing wire was used as the antenna.

940-10 (L. G. Young). Describes an early type of 10-w Chick utilizing noise-controlled frequency modulation. The method depends upon the variation in the inductance of a coil with a Permalloy core whose magnetization is varied at random noise rates, thus varying the frequency of a two-stage oscillator. Development was stopped pending availability of 15-lb 90-amp-hr battery to operate six tubes, including one 884 noise source.

(December 9, 1943)

940-13 (R. C. Shaw, R. W. Friis). Discusses various mechanical designs for a unit that will remain in an upright position after landing, thereby permitting the use of a self-supporting antenna. Complete details are given for a square box type.

(March 20, 1943)

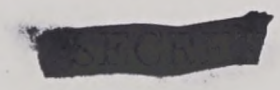
940-14 (J. P. Schafer, L. E. Hunt, G. V. Dale, L. G. Young). Recounts the work done in developing Dina Chick until concluded pending actual Service demand. Details are given with regard to mechanical design, antenna and field strength measurements, and the radio transmitter.

(April 1, 1944)

966-7 (NDRC-15004) (V. A. Douglas). Gives results of *tests of Chick I,* an experimental jammer consisting of a battery-powered ignition coil and spark gap. The device is effective against a-m communications if the receiver is not overloaded or is not equipped with noise-limiting circuits. It has little effect on f-m receivers.

(July 9, 1943)

966-12 (NDRC-15004) (A. C. Peterson). Discusses the *optimum size of Chicks* and concludes



that 1-5 w is best for use over land and 10 w for use over water.

(August 2, 1943)

966-22 (G. J. Heinzelman). Analyzes various *problems in the use of Chicks* as regards number, design, power, bandwidth, and type of signal best suited for various conditions and terrains. The treatment includes the development and application of formulas for determining the required weight and number per unit area, the optimum power and weight of a unit Chick, and the effect of bandwidth on the total weight required for barrage jamming.

(February 5, 1944)

966-28 (G. J. Heinzelman, J. W. Emling). Gives results of *tests on Dina and spark types of Chick* in order to determine the spectra of the r-f interference, the efficiency in converting d-c power to r-f interference, and the effectiveness of communications jamming. (Interference from the spark type is due to the discharge from a spark coil of the vibrating interrupter type.) Under ideal conditions, the results are essentially the same, being generally slightly in favor of Dina.

(June 15, 1944)

2.6 CONTROLLED-DEVICE JAMMING TRANSMITTERS

1.5-Kw Airborne Jammer of Guided Missiles, 20-70 mc.

Div. 15	RP-419a	Army	ARQ-11
AIL	919a	Navy	ARQ-11

This equipment consists essentially of a 20- to 70-mc receiver (R-21/ARQ-11) and a self-excited transmitting oscillator having an average output of about 1,700 w at 20 mc and 400 w at 70 mc. The output is square wave-modulated in the 100- to 15,000-c range. In operation, the oscillator's unmodulated carrier at low power is tuned to the frequency of the enemy transmitter by listening to their difference frequency; the full power output is then keyed at a predetermined audio frequency.

1305-8. Handbook of instructions for audio oscillator O-28/ARQ-11 to supply audio input signals (30-30,000 c) for modulator unit.

(March 19, 1945)

1305-14. Handbook of instructions for radio receiver R-21/ARQ-11 with five tuning units, each covering one of five 10-mc bands between 20 and 70 mc.

(June 30, 1945)

1305-15. Handbook of instructions for C-187/ARQ-11 control unit for distributing power and for PP-130/ARQ-11 rectifier, of which there are three identical 1,000-w units.

(June 30, 1945)

1305-TM 1. Describes the gear reduction unit designed to drive the tuning apparatus in the T-102/ARQ-11 equipment. This provides an accurate vernier dial for heavy loads and has a unique means for eliminating backlash.

(March 27, 1945)

1305-18 (RP-421, 419a, b) (J. N. Fricker, O. H. Schmitt, H. W. DeWeese, R. R. Yost, C. F. Noyes, A. C. Weld). Describes *AN/ARQ-11 and AN/SRQ-11,* with photos and circuit diagrams of all components. AN/SRQ-11 is a ship-borne version of AN/ARQ-11.

(August 31, 1945)

1305-17 (913, RP-389) (O. H. Schmitt, R. G. Madsen, G. D. Sullivan). Describes *AN/SRQ-1 multichannel jammer* to be used against guided missiles in the 46- to 51-mc band. The equipment utilizes eight low-power oscillators, each adjustable to any desired frequency in the band, modulated by a square wave at four audio frequencies and amplified for 10-w broad-band radiation at the frequency of the signals to be jammed. The latter are monitored over the search band and presented on a cathode-ray tube for visual comparison and matching with the locally generated signals. Means are also provided for aural matching for precise tuning. Timing circuits permit operation of the search equipment for 9 μsec and then blank the visual and aural presentations. The transmitter then operates for 90 μsec and the cycle is repeated after a 1-μsec delay to allow the receiver to reach equilibrium after the overload imposed by the transmitter. One prototype was completed and operated.

(August 31, 1945)

MAS Ship-borne Jammer, 41-51 mc. (Division 15, AIL, RP-395, 915).

This manually tuned spot jammer is intended to jam the control signals of the German HS-293 glide bomb and the PC-1400-FX armor-piercing bomb. The equipment consists essentially of an untuned search receiver and a self-excited 150-w transmitting oscillator whose frequency is tuned to that of the enemy transmitter by aid of the search receiver. The jamming signal consists of r-f power automatically keyed 100, 1,500, 8,000, or 12,000 times per second, the modulating frequency being interrupted at 0.1-sec intervals.

1305-3 (R. F. Schulz, D. M. Miller). Describes the enemy missiles and the equipment used to jam

their control systems, including brief operating instructions.

(January 2, 1945)

1305-5. Instruction handbook giving data on operation and maintenance of MAS.

(February 12, 1945)

1305-11 (901, RP-359) (R. F. Schulz, E. W. Adams). Traces the development of four experimental models of *automatic search jammer "Broom"* to be worked against enemy transmissions used to control guided missiles such as radio-controlled glide bombs. The requirement that most of the energy in the radiated signal be concentrated within a 50-kc band in the 45- to 51-mc range was met. It was found, however, that a single Broom could jam only one of two or more signals occurring simultaneously in the search band and that additional Brooms would jam one another unless all were carefully interlocked by a complex system.

(April 21, 1945)

1305-13 (920a, RP-420a) (O. W. Towner, J. W. Wright, P. S. Carter). Tells of the conversion of 50-kw power amplifiers to provide *AN/GRQ-1 jamming equipment* against radio-controlled guided missiles in the 20- to 60-mc range. The chief modifications were the addition of a modulation system to give a square-wave output signal and the addition of a rhombic antenna system. This ground-based jammer was later changed to a truck-mounted mobile installation.

(May 31, 1945)

2.7 MISCELLANEOUS JAMMING TRANSMITTER STUDIES

411-TM-27 (M. T. Lebenbaum). Suggestions for *setting* various jamming *transmitters on frequency.* Any airborne jammer should be accompanied by a suitable monitoring receiver for spot jamming operations. Specific directions are given for tuning B-2000, B-2200, F-902, and F-1500 on the ground and in the air.

626-1 (NDRC project C-56) (D. K. Gannett). Gives results of testing the *effect of interference on reception* of radiotelegraph signals. Complete loss of intelligibility occurs when resistance noise (3-kc band) is 10 db stronger than desired signal; narrowing the band has no effect on per cent errors or point of complete failure. Interference due to sudden change in frequency of c-w transmission causes complete failure when the interfering energy is 2 db stronger than the signal energy; narrowing the interference band increases the required noise level.

(May 27, 1942)

626-2 (NDRC project C-56) (D. K. Gannett). Discusses the *effect of resistance noise on intelligibility* of telegraph signals and speech. Curves are given to indicate the relationship between intelligibility and noise-to-signal ratio in decibels.

(June 2, 1942)

626-3 (NDRC project C-56) (D. K. Gannett). Gives results of testing the *speech-masking effectiveness of various superposed noises.* Resistance noise is found to be more effective than speech babble, stepped tones, sawtooth scanning, trains of impulses, etc., all of which have gaps in their spectra through which fragments of speech may be heard. Complete data are presented in the form of curves and spectrograms showing the degree of masking.

(August 25, 1942)

626-4 (NDRC project C-56) (D. K. Gannett). Finds that the *most effective type of jamming interference* has a spectrum which is continuous in time and in frequency and which has a minimum of interruption for viewing the jammed signal. Application of a-f resistance noise to an f-m transmitter provides a suitable signal for jamming all types of a-m and f-m speech and telegraph channels; the interference bandwidth may be adjusted by changing the degree of modulation.

(September 22, 1942)

778-1 (NDRC project C-63) (W. C. Babcock). Analyzes those types of vertically polarized *electric-wave propagation* which involve direct transmission between a transmitter and receiver plus the effect of ground waves over moist soil. Results are given in the form of curves showing ground-wave field intensity versus distance for various frequencies and heights. Usefulness of the data is illustrated by finding that the relative effectiveness of strong ground-based jammers and weak airborne jammers depends upon the wavelength of the signal to be jammed (airborne equipment is superior at wavelengths of less than 100 m).

(October 19, 1942)

778-3 (NDRC project C-63) (M. E. Campbell). Gives preliminary results of a qualitative investigation of the *effectiveness of f-m jamming signals* against voice and c-w transmission. The conclusions are that a simple f-m signal is not effective against continuous wave on a broad-band receiver and is slightly more effective against voice transmission than is a double-sideband a-m signal.

(April 28, 1943)

778-4 (NDRC project C-63) (A. C. Peterson). Describes a *method for solving transmission problems* associated with the jamming of ground com-

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munications from either the ground or the air. The method involves knowledge of a few simple factors and the use of plotted curves. It is illustrated by a couple of practical examples, such as the maximum distance or minimum height from which a specified installation can be jammed by specified equipment.

(January 27, 1943)

778-6 (NDRC project C-63) (A. D. Fowler). Mathematically analyzes the energy-frequency output *spectrum of a noise-modulated f-m transmitter* and suggests means for improving the spectrum in order to provide a suitable type of *communications jamming signal.* Suggested means involves use of an "erfer" or error function compressor circuit in conjunction with a thermal noise source, a system of low-pass filters, and a frequency modulator.

(January 29, 1943)

778-9 (NDRC project C-63) (K. C. Black). Reviews work done in the *study of communications jamming* as reported in 787-1 to 787-8 and outlines plans for future studies under projects 15004, 15005, and 15006.

(February 1, 1943)

895-5 (P. F. Godley). Presents computed curves of *r-f propagation above the earth's surface.* The curves show the variation in field strength at altitudes between 300 and 40,000 ft for distances of 25, 50, and 100 miles and for a number of frequencies ranging from 0.6 to 600 mc. The general characteristics of the propagation are discussed and contours are drawn to show the location of the first maximum. These curves provide a general picture of wave propagation from aircraft to ground.

(September 11, 1943)

895-8 (RP-263) (W. A. Anderson). Considers the problem of *monitoring and tracking* a victim communications signal that is to be jammed. The most promising of several methods that were investigated is an AFC system which adjusts the jammer to zero beat with the victim signal. This is a servo arrangement utilizing the reversal in phase in the output of a difference frequency modulator which takes place when the two frequencies pass through zero beat. (This proposal ultimately led to the development of "Stopwatch.")

(October 26, 1943)

895-34 (RP-263) (W. A. Anderson). Discusses the design and testing of the *Stopwatch alignment system* for automatically holding a c-w jamming signal to within ± 10 c of a received hand-keyed telegraph signal frequency in the 1- to 20-mc band. The device incorporates the essential components of a radio receiver, transmitter, exciter, and a servomechanism, utilizing a common oscillator to heterodyne with both victim and jammer frequencies and to feed two similar i-f amplifiers. The "sense" of any frequency difference between the two signals is determined by phase detectors which actuate a servomechanism. The spacing periods of the jammer telegraph transmission provide the look-in intervals required to achieve essentially zero beat between the victim and jammer frequencies. Compared with existing jammers, such as random noise or some types of modulation, a jammer equipped with Stopwatch effects a 100 to 1 saving in power requirements.

(January 18, 1945)

1428-1 (RP-263a) (E. Ruth). Summarizes contractor's efforts to deliver finished model of *Stopwatch.*

(December 13, 1945)

1428-2 (RP-263a). Gives preliminary instructions for operating and maintaining *AN/URQ-1* combined receiver and transmitter unit for jamming continuous-wave and modulated continuous-wave signals in the 0.95- to 18.1-mc range.

(December, 1945)

895-18 (RP-263) (W. A. Anderson). Describes the *Quado indicator* to provide visual comparison of two frequencies differing by less than 5 c, such as audio tones obtained when a communications receiver is tuned to a distant code signal and a local jammer. The device consists essentially of a frequency standard and special type of motor-driven neon stroboscope. (Navy tests indicated that the device is not suitable for aircraft use because of its susceptibility to noise and the frequency instability of the receiver beat-note output.)

(April 4, 1944)

895-37 (RP-263) (W. A. Anderson). Describes the *dual Quado indicator* consisting of two strobotrons with means for switching between them so that beats from the distant and local transmitters appear on separate indicators. (The instrument was satisfactory for noiseless signals, but not for the intended application because of difficulty in adjusting the beat note under conditions of noise and random keying.)

(January 27, 1945)

940-8 (RP-235) (W. J. Albersheim). Describes and discusses *barrage-jamming tests with r-f noise* obtained by Dina (direct-noise amplification), by frequency modulation, and by Pad (noncoherent pulses). Tests using speech modulation were conducted against double-detection and superregenerative amplitude-modulated receivers and a frequency-modulated receiver. A few spot tests indicated that noise power required to jam telegraph

code is nearly six times higher than speech jamming level. Detailed quantitative report of results can be approximately summarized by statement that Dina seems to be superior to other methods.

(October 20, 1943)

ANTIJAMMING

3.1 COMMUNICATIONS ANTIJAMMING

411-20 (K-100, RP-126) (A. E. Cullom). *Laboratory experiments on vulnerability of Loran* navigational system (1.95 mc) to various types of jamming. The tests indicate that the J/S ratios (peak jam to peak signal) required for effective jamming are approximately as follows: Dina, 7.4 db; noise (2-36 kc) 100 per cent AM, 10 db; noise (2-36 kc) FM, (150-kc swing), 14 db; sine wave (12 kc) 100 per cent AM, 18-30 db; sine wave (6 kc) FM, (75-kc swing), 18-32 db. The general conclusion is that Loran is difficult to jam effectively. The report includes performance curves and sketches of scope patterns.

966-1 (NDRC-15004) (A. C. Peterson). Presents generalized radio propagation curves for *estimating jammer effectiveness* at various heights or distances or for various radii of area at frequencies varying from 0.6 mc to 600 mc.

(March 16, 1943)

966-2 (NDRC-15004) (R. B. Shanck, V. A. Douglas). Discusses the effectiveness of various methods of *jamming radiotelegraph reception.* Preliminary tests lead to the conclusion that continuous-wave [c-w] carrier signals can be most effectively jammed by c-w signals closely corresponding to the telegraph signals. Several objections to this method cause preference to be given to AM of suppressed jamming carrier with resistance noise falling within a narrow hand about signal carrier.

(March 29, 1943)

966-3 (NDRC project 15004) (H. H. Benning). Summarizes aptitude tests of experienced operators in reading through various types of *signals used to jam telegraph communications.* Listed in the order of their c-w jamming effectiveness, the signals are (1) keyed carrier within 2-10 c of the victim's carrier (a completely impractical condition), (2) amplitude modulation with noise, carrier suppressed, (3) r-f noise, (4) amplitude modulation with noise, carrier transmitted, (5) frequency modulation with noise, (6) r-f impulses at a-f rate, (7) stepped tones.

(August 22, 1943)

966-6 (NDRC-15004) (A. C. Peterson). Explains a method for the *solution of transmission problems* associated with the jamming of ground communications. The method is an extension of that described in 778-4 (see Section 2.7).

(May 22, 1943)

966-6C (NDRC-15004). *Handbook of propagation curves* for estimating the received field intensity of ground-wave signals in 200-kc to 600-mc range.

(October, 1944)

966-9 (NDRC-15004) (V. A. Douglas). Gives results of laboratory *tests of AN/ARQ-2* (Jackal). The general conclusions are that the device is ineffective in jamming f-m receivers and a-m receivers equipped with noise limiters.

(August 10, 1943)

966-11 (NDRC-15004) (H. H. Benning). Discusses the comparative *vulnerability of a-m and f-m communications,* concluding that f-m systems, especially when crystal-controlled, are easier to jam than are a-m systems equipped with limiters.

(July 28, 1943)

966-18 (Project 15004) (W. C. Babcock). Considers the theoretical requirements for effective *jamming of German GCI* ground-to-plane communications in 38.6- to 42.2-mc range by means of equipment carried by 60 bombers. Complete blockout on a barrage basis from any point within the control area would require 2.1 kw of r-f power per bomber, corresponding to about 350 w per channel. With 75 w or more per channel, flight directly over the GCI provides the greatest jamming coverage. The shortest distance over which a bomber formation can attain coverage is indicated by the direction of the GCI; this distance can be maximized by flight along the boundary line of adjacent control areas. Spot jamming should be more effective than barrage jamming, particularly with low power.

(October 22, 1943)

966-20 (Project 15004) (V. A. Douglas). Recommends various changes as a result of *tests of the effectiveness of AN/ARQ-2* equipment. The most important changes are the removal of the noise modulation on the condenser unit and the use of a 500-c rotating condenser sweep instead of the short-circuited turn. Test results are presented in detail.

(October 22, 1943)

966-21 (RP-109) (K. G. Jansky). Concludes that certain *enemy "see-saw" signals* recorded by U.S.A. observers are probably radiated from rotating beacon stations for navigational use by sub-

SECRET

marines or airplanes in 300-1,000 determination of location by bearings from two stations.

(November 10, 1943)

966-24 (RP-109) (H. H. Benning). Finds that the AJ *effectiveness of vacuum-tube limiters* (clipper-slicer type) is very slight on random or natural noise.

(December 28, 1943)

966-25 (RP-109) (V. A. Douglas, E. O. Bernard, M. I. Risley). Gives test curves on *effectiveness of mechanical f-m jammers against a-m voice links* (particularly Fu Ge 16, which is described in detail) in the 38- to 42-mc range. The signal from a single sweep-type jammer is found to be less effective than that from a noise-modulated jammer but can be slightly enhanced by varying the sweep rate. Loss of effectiveness due to limiting devices in receiver can be partly overcome by barrage from several sweep jammers covering entire frequency band.

(April 7, 1944)

966-26 (RP-109) (C. R. England). Gives results of studies of a *multicarrier homodyne signal for jamming c-w telegraphy*. The signal is generated by automatically keying a multivibrator alternately "on" and "off" for prescribed time intervals; the squared up output pulses modulate a 4-mc oscillator. Depending upon the keying rate and the percentage of "on" time the device produces a 120- to 160-c band spectrum consisting of six to eight carriers with a 20-c spacing. The resultant jamming signal appears to be about as effective as a band of random noise having the same narrow width.

(May 22, 1944)

966-30 (RP-109) (V. A. Douglas). Finds the *jamming effectiveness of AN/ART-2 against a-m nets* to be slightly less than that of f-m noise. The effectiveness is not lessened by audio limiters nor Lamb type noise suppressors. The equipment provides about 1.5 w of useful energy in interfering with a 10-kc channel.

(May 9, 1944)

966-31 (RP-109). Outlines technical considerations underlying *effective jamming and AJ of radio communications*. The important characteristics of telephone and telegraph signals, the hearing sense, receivers, and various types of jamming signals are discussed. Ground-wave and sky-wave propagation are described with respect to transmission to and from aircraft. The influence of antenna efficiency, bandwidth, and directivity is considered, as are also the various factors which must be taken into account in determining range. Discussion of AJ methods is brief. The report with its many diagrams provides an excellent introduction to a study of the jamming of radio communications.

(May 16, 1944)

966-32 (RP-109) (V. A. Douglas). Reports on the *vulnerability of f-m communications receivers* to mechanical f-m barrage jamming. Tests indicate that SCR-608, -609, and -808 are more susceptible to the blocking oscillator sweep-type jammers than to the simple sweep type. Detailed analyses show that American f-m systems may be disrupted by mechanical f-m jamming of German a-m communications.

(August 1, 1944)

966-33 (RP-109) (R. B. Shanck). Gives results of controlled tests of the comparative ability of experienced and inexperienced operators in the *reception of telegraph signals through interference* by random noise and five-tone Bagpipes. The former displayed greater uniformity in ability than did the latter. Random noise was less tolerable than Bagpipes.

(October 18, 1944)

966-34 (RP-109) (M. C. Francis). Gives results of flight tests of the *jamming effectiveness of SCR-8* modulated with random noise. This airborne 25-w f-m transmitter operated against a 10-w 10 WSc transmitter in a moving truck and a stationary UKwEe receiver. Preliminary results indicated satisfactory jamming in the 27- to 38.9-mc range.

(May 20, 1944)

966-35 (RP-109) (W. A. Getchell, G. J. Heinzelman, J. L. Lindner). Reports on *effects of jittering the sweep modulation of mechanical f-m jammers.* Jittering causes an improvement of about 4 db in jamming effectiveness, which is greatly decreased by limiters. The effect is practically independent of sweep rates varying from 50 to 100 c except at exact multiples of 100 c, when the effect is the same as that due to nonjittered signals. The latter are most effective at 100-200 c and 3,000-4,000 c.

(August 1, 1944)

966-40 (H. H. Benning). Discusses general considerations governing *RCM against Japanese communications,* particularly as regards choice between intercept and jamming and as regards jamming of friendly communications. Airborne barrage jammers appear to be of little use in the 1.20-mc band and should be used in the 20- to 100-mc band only when friendly communications can be sacrificed. Chicks are useful in jamming some fixed point.

(September 29, 1944)

966-41 (RP-109) (G. J. Heinzelman, J. L.

Lindner). Gives results of tests of *susceptibility of Japanese Model 99 type Hi3* airborne radio set. Susceptibility to jamming from random noise or stepped tones is found to be about the same as that of an American a-m link using a receiver without noise limiters. The Japanese set is somewhat more susceptible to interference from an unmodulated carrier.

(November 13, 1944)

966-42 (RP-109) (G. J. Heinzelman, J. L. Lindner). Gives results of testing the *jamming susceptibility* of Japanese No. 775 meteorological receiver. Frequency-modulated carrier and frequency-modulated random noise are found to be more effective than amplitude modulation or amplified random noise.

(December 9, 1944)

966-44 (RP-148) (R. L. Robbins). Describes a simple type of *noise generator for "static burst" jamming* to cause an enemy operator to ask for a repeat of a message which has been obscured while being copied by radio intelligence. Noise generated by the burning of minute contact areas by current passing through a cartridge of loose carbon particles is used to modulate the output of a transmitter thus employed to simulate static.

(December 21, 1944)

966-45 (RP-109) (G. J. Heinzelman). Finds that the *jamming susceptibility of Japanese 99 Mark IV* airborne phone set for 44- to 50-mc range is greater than that of other tested superheterodyne receivers without noise limiters.

(January 20, 1945)

966-46 (RP-109) (G. J. Heinzelman). Finds that the *jamming susceptibility of Japanese Mark V* portable receiver for 0.4- to 7-mc range is substantially the same as that of a conventional a-m superheterodyne excepting for greater susceptibility to spark and sweeping carrier interference.

(February 7, 1945)

966-49 (RP-109) (G. J. Heinzelman, E. O. Bernard). Finds that the *jamming susceptibility of Japanese TM 305 C1* mobile receiver for 19.6- to 30.6-mc range is relatively great for all types of interference.

(February 8, 1945)

966-56 (RP-109, -115, -132, -148, -149, -150, -233, -259, -272B, -326, -358, -410, -422, -440) (M. L. Almquist, R. P. Booth). Outlines the general problems encountered in *radio communications countermeasures* and summarizes the investigations reported in 966-1 to 966-55.

993-1 (RP-122) (H. M. Straube). Discusses *the theory of automatic tuning of jammers*. The discussion covers automatic frequency alignment by a tracking system which is stabilized to provide minimum drift by a feedback stabilized system and by modulated signal operation.

(August 13, 1943)

993-2 (RP-122) (E. R. Taylor). Describes preliminary design for an airborne *multiple spot-jamming system* whereby from one to four AN/ARQ-9 may be simultaneously operated in one aircraft in order to jam the same number of communication channels. Facilities are provided for narrow-band and broad-band monitoring. To aid in observation of enemy signals the transmitters and frequency scanners are synchronously controlled.

(August 23, 1944)

993-3 (RP-122) (E. R. Taylor). Discusses problems associated with *listening through and aligning spot jammers* on victim frequencies. Detailed consideration is given to broad-band and narrow-band scanning problems as typified by the design and performance of the 18- to 80-mc scanning receiver in AN/ARQ-9 and the 1.85- to 18.5-mc narrow-band receiver in SCR-596-T2. Considerable attention is given to the choice of methods for minimizing spurious responses and to design improvements based upon performance under abnormally severe conditions. The report includes typical circuit diagrams and performance curves.

(June 8, 1945)

778-7 (NDRC project C-63) (K. C. Black, W. H. Wise). Considers the *vulnerability of various pulse communications to resistance noise*. It tentatively concludes that pulse frequency modulation is less vulnerable than pulse amplitude or pulse width modulation and that pulse communication is less susceptible to barrage jamming with noise than are the more conventional forms of transmission.

(January 30, 1943)

895-4 (RP-131) (M. G. Crosby). Compares the *readability of f-m, a-m, and telegraph systems* as an index of their relative communication efficiencies when jammed by random noise, impulse noise, and c-w interference. With random noise, the most effective form of interference, telegraphy is most readable, narrow-band FM second, wide-band FM third, and AM fourth in relative readability. Insertion of an audio limiter in the transmitter input improves a-m reception in the presence of random and impulse noise but has little effect for other systems and types of interference. Removal of the f-m limiter at the receiver has little effect with random noise, gives greater interference from im-

SECRET

pulse noise, and, for critical tuning, improves reception in the presence of audible c-w interference. Critical tuning of the f-m receiver improves readability.

(August 24, 1943)

895-6 (RP-131) (M. G. Crosby). Describes the circuit of a *differentiating and limiting amplifier* used to raise the apparent volume level of voice communication. (See 895-4.) The device clips the higher peaks and raises the amplitude of the low-level portion of a voice wave.

(September 30, 1943)

895-7 (RP-131) (W. H. Bliss). Gives test results on the *performance characteristics of ARC-1* receiver, including frequency bandwidth and noise characteristic curves. The noise level is found to be high, whence the effective sensitivity is low. The lack of single-dial tuning is disadvantageous for general signal hunting, since weak signals may be missed.

(October 22, 1943)

895-19 (RP-131). Instructs on the use of *narrow-band f-m adapter for BC-603-D* receiver under conditions of low signal strength, high noise level and radio interference. Its 8-kc band is accepted with only a slight sacrifice in the quality of speech reproduction.

(April 26, 1944)

895-41 (RP-123, -131, -198, -227, -228, -229, -230, -231, -252, -260, -263, -325, -345, -352, -420b, -460) (H. H. Beverage). Recapitulates *jamming and AJ techniques* investigated under contract 895. In addition to these projects for which separate reports are given (and digested), the report includes accounts of preliminary studies of (1) expendable transmitter "Hen" for propaganda broadcasting, (2) an electrical cancellation and indicating system for submarine detection and panoramic presentation of radio and radar signals, and (3) antenna system for ground-based jammer of guided missiles.

(October 10, 1945)

895-14 (RP-123) (J. B. Atwood, G. E. Hansell). Discusses *jamming and AJ tests of a pulse phase-modulation system* of voice communication. For a receiver whose circuit details are not known the most effective jamming signal is found to be an r-f spectrum of random noise gated 50 per cent covering the receiver's i-f bandwidth. Phase-modulated pulses and c-w jamming were also tested. When the receiver is known to have certain circuit arrangements, savings up to 26 db in jamming power may be obtained. The most effective AJ device is a pass circuit which is selective as to both the amplitude and the slope of the pulse.

(February 16, 1944)

895-25 (RP-123) (J. B. Atwood, G. E. Hansell). Describes the *pulse amplitude selective automatic gain control circuit* whose pass portion was used in the AJ tests discussed in 895-14. The automatic gain control circuit maintains the receiver gain at the proper level in the presence of strong interfering pulses. The pass circuit responds to a narrow range of pulse amplitudes and does not transmit pulses of higher or lower amplitude. The combination of the automatic gain control and pass circuit provides communication reception which is relatively free from jamming.

(July 22, 1944)

895-26 (RP-123) (J. B. Atwood, G. E. Hansell). Describes *f-m pulse jamming tests of a pulse phase-modulation system* of voice communication. Comparison with the results of phase-modulation pulse jamming (see 895-14) show definite power savings for FM. If the circuit details of the receiver to be jammed are not known, an r-f spectrum of random noise gated 50 per cent is still the most effective jammer.

(August 7, 1944)

895-30 (RP-123) (J. B. Atwood, G. E. Hansell). Finds that the effect of *noise jamming of a pulse frequency-modulation system* of voice communication is to vary the width of the pulse and thus greatly reduce the signal-to-noise ratio. Circuits for eliminating the variation in width are shown and a formula is derived to give the improvement thus obtained in the signal-to-noise ratio.

(October 25, 1944)

895-36 (RP-123) (J. B. Atwood, G. E. Hansell). Describes two types of *short-pulse f-m receivers* and discusses their susceptibility to various kinds of jamming signals. One type of receiver using a trigger circuit and low-pass filter for detection is easily jammed. In the other type of receiver the pulses are converted into sine waves which are passed through a double limiter and a discriminator. The report concludes the investigations of jamming and AJ tests previously reported, making no radical change in conclusions.

(January 23, 1945)

895-12 (RP-228) (C. N. Gillespie). Evaluates the *AJ characteristics of a facsimile transmission system* in which a narrow-band amplitude-modulated receiver is used with a wide-band frequency-modulated transmitter modulated by a black and white signal. The receiver detects a pulse

each time its pass band is swept by the frequency-modulated signal, thus recording only the edges or transients of the original picture. Studies indicate that the consequent loss in detail inherent in the "transient system" is not counterbalanced by the improved signal-to-noise ratio. The transient system also requires very precise operating adjustments of background. Existing facsimile type systems are thus fully as satisfactory with respect to operation under jamming conditions.

(January 12, 1944)

895-13 (RP-227) (J. A. Spencer). Discusses means for improving the *AJ characteristics of printing telegraph systems,* particularly the five-unit start-stop teletype and the seven-unit radio printer. The systems are found to be less vulnerable to fluctuation noise than to square-wave impulses. The most satisfactory AJ circuit arrangement includes space diversity reception, two-tone frequency-modulated keying and seven-unit operation employing synchronous transmission with front-end correction and collation (transmission and reception of each character code combination several times).

(January 15, 1944)

895-20 (RP-229) (E. R. Shenk, J. A. Spencer, E. B. Anderson). Discusses the *AJ characteristics of Beechnut,* a British system of ideograph transmission for communication between ground and aircraft. Tests demonstrate that this system can be effectively jammed by: (1) jamming carrier having half the amplitude of the desired carrier and 100 per cent modulated by a superaudio tone whose frequency is approximately equal to the frequency of the Beechnut transmitted marking tone; (2) unmodulated jamming carrier having three-fourths the amplitude of the desired carrier and differing from it in frequency by the frequency of the marking tone. The use of fluctuation noise or barrage jamming is found to be relatively ineffective.

(April 15, 1944)

895-28 (RP-229) (J. E. Smith, E. R. Shenk, J. R. Weiner). Finds that the *demodulating effect* of a strong jamming signal upon a weak desired signal, when both are simultaneously present in the input of a linear detector, can be largely overcome through the use of a capacitor in shunt with the detector load resistor. Such a peak detector is most useful when the frequency difference of the two carriers is three or four times the maximum desired modulation frequency, a condition which often exists in u-h-f receivers. Care must be used in designing the first audio coupling network and automatic gain control filter circuit when the jamming carrier is keyed.

(September 18, 1944)

895-39 (RP-229) (J. E. Smith, J. A. Spencer, E. R. Shenk, L. P. Reinhold). Describes the *Voflag impulse signaling system* of radio communication between a base station and a multiplicity of aircraft. The system is designed to be less susceptible to jamming than is the British "Beechnut" system for ground-to-aircraft communication by displaying a six ideogram message before the pilot. The Voflag uses two-tone polar telegraph keying with an error-proof code having the characteristics of an automatic telegraph. Provision is made for both manual acknowledgment and automatic answer back. An attachment to the airborne portion permits the recording of a printed message in addition to the visual display.

(October 24, 1945)

895-38 (RP-460) (B. A. Trevor). Describes the apparatus and procedure in determining the *jamming characteristics of AN/TRC-5* pulse communication system. The system is found to be relatively invulnerable, since effective jamming requires an airborne jammer situated within a narrow range of angles, thus limiting the jamming time for inferior air power. The most effective jamming occurred at about a 10-kc pulse rate with 1- or 2-μsec pulses. The report includes AJ suggestions.

(May 29, 1945)

895-42 (SO-26005, RP-460). Finds that *phototube demodulation of time division multichannel pulsed signals* which are synchronized on a cathode-ray tube is not a satisfactory method for identification and analysis with airborne equipment. Tests were made with signals from AN/TRC-5 viewed on AN/APA-11 and on 715A oscilloscope. Intelligible modulation requires a very bright trace on a cathode-ray tube at least 5 in. in diameter and is then rather noisy.

(October 17, 1945)

936-1 (RP-159) (E. Labin, D. D. Grieg, R. B. Reade). Discusses the problems and factors involved in the *jamming and antijamming of radiotelegraphy.* The discussion covers the results of exhaustive tests of all types of jamming at both audio and radio frequencies and also covers AJ studies involving the use of protective limiters for telegraph receivers. The conclusion is that limiters are effective against noise signals that interfere with idealized laboratory receivers.

(September 10, 1943)

936-2 (RP-159) (E. Labin, D. D. Grieg, R. B.

Reade). Discusses the results of further studies of the *jamming and antijamming of radiotelegraphy.* The reported results are for jamming tests without limiter against Navy RBC-1 and Army BC-342-N receivers and for AJ tests of the receivers with protective limiter. The significant conclusions are that the existing internal limiters of the RBC-1 are ineffective against resistance noise jamming, that maximum AJ improvement is obtained by placing a clipper-type limiter between the last i-f stage and first a-f stage of the receiver, and that the improvement in reception due to the limiter action is vitiated by keying the clipped noise jamming signal at a code speed rate.

(April 1, 1944)

936-3 (RP-159) (E. Labin, D. D. Grieg, R. B. Reade). Gives results of *jamming telegraphy with keyed noise* compared with those obtained with unkeyed noise. The general conclusion is that any effective jamming signal may be keyed on and off without reducing its effectiveness, provided that due respect is paid to the adjustment of duty cycle and keying rate. In other words, the effects of keying are independent of the spectrum of the uninterrupted modulated jamming signal.

(July 25, 1944)

936-5 (RP-159) (H. H. Buttner). Summarizes the results of experimental *jamming and AJ of telegraphy.* In addition to data from 936-1, -2, -3, and -4 (see above and Section 1.4) this report tells of assistance given in field tests of Radio Research Laboratory [RRL] models and of evaluation tests of Navy XGE modulator used as a jammer.

(April 30, 1945)

937-1 (RP-124) (S. H. Dodington). Proposes a program for developing a *radio communication system protected against interference* by jamming voice channels in the 2- to 9-mc range. The general plan calls for some form of radio printer, several types of which are described.

(February 19, 1943)

937-2 (RP-124) (E. M. Deloraine). Discusses preliminary results obtained in developing a *protected communication system* to withstand jamming. In place of voice communication, the system employs a nine-frequency printer (to obviate need for training operators in Morse code under jamming conditions) and a two-frequency peak rider circuit to eliminate "apparent demodulation." As the latter is only partially effective, development will be continued.

(April 28, 1944)

937-3 (LD51-301, RP-124) (H. Busignies, S. H. Dodington, J. A. Herbst, G. R. Clark). Describes a two-way aircraft *radio communication system partly protected against interference.* Protection is afforded by audio filters which select only those frequencies which are conveying intelligence and reject all other components of the audio signal. As the method precludes voice communication, a tape printer is employed to present a visual message sent by means of a keyboard resembling that of a typewriter. The printer will operate through noise-modulated jamming or atmospheric noise that is about 11 db stronger than the desired signal.

(July 12, 1945)

1024-1 (RP-189) (S. L. Bailey). Discusses *vulnerability of FuGe receiver to Cigar type of jamming* with frequency-modulated signal. It is concluded that the jamming effect is primarily due to listener fatigue and only secondarily to distortion of intelligence in the circuits of the receiver.

(January, 1944)

1024-2 (RP-189) (R. H. Culver). Recounts the development of a reliable *gas-tube noise generator circuit* using a type 2050 tube to produce a 20-kc band of noise uniformly.

(January, 1944)

1024-3 (RP-189) (D. C. Ports). Discusses methods for *decreasing susceptibility of f-m receivers to c-w jamming.* The most effective method is found to be a back-biasing system applied to one stage of the i-f amplifier designed with a sharp cutoff. The bias should be automatically adjusted to approach cutoff in order to eliminate the capture effect and yet recover enough of the original speech in the distorted output to make it intelligible.

(March, 1944)

1024-4 (RP-189) (O. W. B. Reed). Reports the results of *jamming tests against BC-603-D* receiver as used in mobile f-m radiophone equipment. It is found that this receiver may be jammed by a step tone of noise f-m jammer when interference deviation fills the receiver pass band and has a field strength equal to that of the desired signal. An improvement of 2-5 db may be obtained by increasing the deviation of the desired signal.

1024-5 (RP-189) (F. T. Mitchell, P. F. Hoffmann). Gives results of *jamming tests against BC-659-B* receiver in the SCR-609-A portable transceiver. Frequency-modulated jamming with noise or stepped tone is found to be most effective against this f-m equipment.

(May, 1944)

1024-6 (RP-189) (O. W. B. Reed, E. H. Scheibe). Gives results of preliminary *jamming tests against*

BC-624-A airborne receiver. The noise suppressor developed by the American-British Laboratory of NDRC Division 15 [ABL-15] now incorporated in the receiver is found to be entirely satisfactory.

(June, 1944)

1024-7 (RP-189) (O. W. B. Reed, E. W. Scheibe). Gives results of *jamming tests against AN/TRC-1* field teletype equipment used in conjunction with Signal Corps four-channel carrier-telephone system. The equipment is found to be more or less vulnerable to all conventional types of jamming. Defense may be afforded by switching to one of the other three channels, all of which should always be available.

(June, 1944)

1024-8 (S. L. Bailey, W. J. Albersheim, M. L. Almquist, H. H. Benning, V. A. Douglas, J. W. Emling, J. H. Moore). Suggestions for standardized definitions and methods of *testing effectiveness of communications jamming*. They represent practice at Bell Telephone Laboratories, Inc., and Jansky & Bailey Laboratory.

(July, 1944)

1024-9 (RP-189) (P. F. Hoffmann). Gives results of *jamming tests against BC-1000-A* receiver in SCR-300-A portable transceiver in 40- to 48-mc range. It is vulnerable to f-m jamming with noise or stepped tunes and to continuous wave.

(August, 1944)

1024-10 (RP-189) (O. W. B. Reed, E. H. Scheibe). Gives results of *jamming tests against 233A* airborne transceiver in 100- to 156-mc range. The set is found to be quite vulnerable.

(October, 1944)

1024-11 (RP-189) (O. W. B. Reed, E. H. Scheibe). Gives results of *jamming tests against BC-639-A* ground receiver in 100- to 156-mc range. The receiver compares favorably with other receivers in this frequency range.

(September, 1944)

1024-12 (RP-189) (O. W. B. Reed, E. H. Scheibe). Gives final results of *jamming tests against BC-624-AM* receiver in 100- to 156-mc range. Better performance against pulsed carriers is provided by a new noise suppressor. Performance against frequency-modulated and continuous-wave jamming is not so good.

(September, 1944)

1024-13 (RP-189) (O. W. B. Reed, E. H. Scheibe). Compares *vulnerability of 233A, BC-624-AM, and BC-639-A* a-m airborne receivers to various types of jamming. The general conclusion favors the incorporation of noise limiters.

(October, 1944)

1024-14 (RP-189) (P. F. Hoffmann). Gives results of testing the vulnerability of BC-348-R airborne amplitude-modulated receiver in 0.2- to 0.5-mc and 1.5- to 18-mc ranges. The receiver is most vulnerable to FM by noise or stepped tones of low deviations. Pulsed carrier jammers are relatively ineffective, as is likewise c-w jamming.

(November, 1944)

1024-15 (RP-189) (D. C. Ports). Finds that 12- to 24-db *peak clipping of audio voltages before modulating* in a communications transmitter improves the intelligibility of reception through noise-modulated f-m jamming.

(December, 1944)

1024-16 (RP-189) (E. H. Scheibe). Gives results of *jamming tests against BC-342-N and BC-312-N* ground-based receivers in 1.5- to 18-mc range. They are found to be more susceptible when used for voice than when used for continuous-wave or modulated continuous-wave communication. An f-m jammer modulated with step tones is most effective against voice communication.

(December, 1944)

1024-17 (RP-189) (F. T. Mitchell). Gives results of tests of the *jamming effectiveness of modified step-tone jammer* having a peak clipper and five tones in the 500- to 700-c range plus a 180-c note instead of five tones in the 300- to 600-c range. The modification is found to improve the effectiveness when the jammer is tuned to zero beat with the signal. The a-m jammer, however, is found to be less effective than an f-m jammer.

(January, 1945)

1024-18 (RP-189) (P. F. Hoffmann). Gives results of *jamming tests against BC-625-A* mobile receiver in 2- to 6-mc range. Continuous wave and modulated continuous wave are found to be harder to jam than voice communication, which is easily jammed by FM.

(January, 1945)

1024-19 (RP-189) (O. W. B. Reed). Gives results of *jamming tests against BC-699-C* receiver in 1.68- to 4.45-mc range. The receiver is found to be most vulnerable to f-m jammers with step tones or noise at low jammer bandwidths.

(January, 1945)

1024-20 (RP-189) (O. W. B. Reed). Gives results of *jamming tests against BC-654-A* mobile receiver in 3.8- to 5.8-mc range. Susceptibility is much the same as that of BC-699-C.

(January, 1945)

1024-21 (RP-189) (P. F. Hoffmann). Compares *vulnerability of BC-348-R, -342-N, -312-N, -652-A*.

SECRET

-669-C, -659-A. In general, BC-348-R is found to be superior to the others.

(February, 1945)

1024-22 (RP-189) (E. H. Scheibe). Gives the *operating characteristics of SCR-536* portable press-to-talk radiophone in 3.5- to 6-mc range. Performance is found to be generally satisfactory.

(February, 1945)

1024-23 (RP-189) (E. H. Scheibe). Gives results of *jamming tests against AN/ARC-1*, original and modified to reduce effectiveness of pulsed carrier interference. The modification results in improved J/S ratios for wide-sweep f-m and pulsed carrier jammers. For other types of jamming no improvement is effected.

(March, 1945)

1024-24 (RP-189) (D. C. Ports). Summarizes data on the *AJ characteristics of f-m communications receivers*. Pulse-type jamming signals are found to be ineffective in reducing intelligibility. Severe jamming is caused by FM having a deviation approximately equal to half the pass band of the receiver. An f-m receiver is also rather vulnerable to other types of jamming. The report discusses design features that contribute toward the most efficient AJ operation.

(March, 1945)

1024-25 (RP-189) (P. F. Hoffmann). Gives results of tests of the *vulnerability of ARB* aircraft receiver in 195- to 9,050-kc range. The receiver is found to be susceptible to all the conventional types of jamming except pulse jamming at low repetition rates.

(May, 1945)

1024-26 (RP-189) (O. W. B. Reed). Reports on the electrical *characteristics and vulnerability of SCR-511-B* receiver in 2- to 6-mc range. The characteristics are found to be generally satisfactory. The receiver is more susceptible to jamming than other ordinary communication gear covering a comparable frequency range.

(June, 1945)

1024-27 (RP-189) (P. F. Hoffmann). Discusses *use of J/S ratio in r-f pulse jamming tests*. This ratio, expressed in decibels, is that of peak pulse jammer power to signal carrier power in the transmission medium at the receiver. The use of this ratio is illustrated in a method for indicating the field intensity at the receiving antenna during the time that the jamming transmitter is pulsed "on." The report also discusses the results of tests showing the decrease in *vulnerability of ARB receiver with Goodyear limiter*.

(July, 1945)

1024-28 (RP-189) (E. H. Scheibe). Gives results of further study of *AN/ARC-1 electrical circuits*. Excessive noise at low signal levels was found to be caused by too rapid AVC action on the r-f stage. Modifications to reduce it are suggested.

(August, 1945)

1024-29 (RP-189) (O. W. B. Reed). Discusses the electrical characteristics and *vulnerability of AN/TRR-2* transportable equipment consisting of a radio receiver designed to pass only a definite r-f signal having specific a-f modulation and an electromechanical switch to detonate a mine when a definite sequence of pulses is received from an activating transmitter (AN/TRT-1). Tests indicate that a simple barrage jammer will prevent the system's operation, either falsely or when required. The extreme vulnerability is found to be due to the use of tone selection and impulse keying combined with a superregenerative receiver.

(September, 1945)

1024-30 (RP-109a) (E. H. Scheibe). Reports on the *vulnerability of the Japanese model 96 Mark 4E* transmitter-receiver in 4- to 4.9-mc range. The receiver is found to be more susceptible when used for voice communication than for continuous wave, the most effective jammers being amplitude-modulated tuned to zero beat with the desired carrier.

(September, 1945)

1024-31 (RP-189) (E. H. Scheibe). Gives the *electrical characteristics of AN/TRC-8* consisting of f-m receiver R48/TRC-8 and f-m transmitter T30/TRC-8 with power peak. The equipment operates in the 230- to 250-mc range, for which equipment was not available for making vulnerability tests. The characteristics are such that it is predicted that the receiver cannot discriminate against f-m jamming, is susceptible to c-w jamming, and has low vulnerability to jamming by pulsed carrier interference.

(September, 1945)

1024-32 (RP-109a) (P. F. Hoffmann). Gives results of preliminary tests of *vulnerability of Japanese Model B* mobile transmitter-receiver. The equipment is found to be more susceptible to jamming than are similar units used by U. S. Armed Forces. Its performance characteristics are likewise inferior, particularly as regards modulation capabilities.

(September, 1945)

1024-33 (RP-189) (S. L. Bailey). Gives results obtained in testing *vulnerability of AN/SWR-2 receiver* designed for use aboard boats to be remotely controlled by an airborne transmitter. The

equipment is found to be extremely vulnerable to c-w jamming, since the control signals are tones which are selected by filters in the receiver. The receiver is also quite vulnerable to pulses. Simple changes are suggested for reducing susceptibility to pulse jamming.

(October, 1945)

867.6 (RP-318) (M. M. Freundlich). Discusses the *use of dark-trace tubes for integration* in scope detection of weak signals. (A dark-trace cathode-ray tube provides slow decay of an image on an alkali-halide screen.) Experimental results indicate a possible slight advantage which does not warrant discarding conventional tubes before dark-trace tubes are improved.

(December 16, 1943)

3.2 RADAR ANTIJAMMING

411-24 (E-200, RP-171) (O. G. Villard). *Laboratory tests in jamming SCR-268* (Type A presentation) with continuous wave, pulses, amplitude modulation, and noise. Reasons for observed behavior are given, as are also suggestions for AJ procedure. The general conclusion is that the general direction and range of the target and jammer can usually be determined while the radar is being jammed with any of the types of signal under test. The report includes photos of scope patterns for various values of jamming field strength in microvolts per meter at the radar mount.

411-36 (E-300, RP-222) (O. G. Villard, S. F. Kaisel). *Laboratory tests in jamming SCR-521A* (176-mc ASV radar). The general conclusions are that noise provides the most effective jamming signal, that jamming effects can be minimized by adjusting receiver gain control to provide optimum response from the target, and that the pip can often be restored by slightly detuning the local oscillator. The r-f selectivity and shielding are such that a radar system can be jammed only by a signal tuned close to its carrier frequency. The report includes photos of scope patterns.

411-53 (E-500, RP-224) (D. R. Scheuch, S. F. Kaisel). Laboratory tests in jamming Mark IV (700 mc). Comments duplicate those for 411-36.

411-41 (A-1200) (E. W. Schuler, J. J. Livingood, J. H. Woodruff). *Laboratory experiments in jamming Type A and plan-position indicator [PPI] presentations of ASG-1* (SCR-617) 10-cm radar by means of klystron transmitter and 30-in. paraboloid. It is concluded that (1) ASG-1 can be jammed so as to prevent determination of range but not prevent determination of direction, (2) one-channel set is more vulnerable than two-channel set, (3) filters will reduce effectiveness of c-w jamming but not of short pulse jamming, (4) 10 db less power is required for jamming with 100 per cent amplitude modulation than with continuous wave, (5) available klystrons not powerful enough to jam 360 degrees of PPI scope. The report includes photos of screen images for various types of jamming.

411-42 (L-400, RP-172) (J. H. Woodruff). *Tests on susceptibility of ASG* (Army SCR-617) to various types of jamming. The general conclusion is that this 10-cm airborne radar is satisfactory with respect to its ability to operate in the presence of enemy jamming. The use of the gain control is an effective AJ measure for c-w jamming, and where the jamming is very strong it is always possible to DF on the jammer. For both noise and sine-wave a-m jamming, reduction of receiver gain is useful. Noise and sine-wave f-m jamming do not reduce the effectiveness of slightly detuning the receiver's local oscillator as an AJ measure.

411-TM-107 (L-105, RP-385) (W. W. Farley). *Field tests with L-105 jamming signal generator against Mark 8* (fire-control) radar. The L-105 consists of a 410-R klystron (20-w unmodulated) with associated regulators and power supplies. The modulation source was a sine-wave oscillator (120 c-200 kc). The results of limited tests indicated that the generator can do the jobs for which it was designed.

411-72 (L-900, RP-277) (J. H. Woodruff). *Laboratory tests of jamming susceptibility of SCR-717B* (10-cm airborne radar). The artificial jamming signals were produced by a type 417 reflex klystron master oscillator followed by a type 411 klystron power amplifier and modulator. Sine-wave and noise AM and FM were used. Except as to its video amplifier this radar was found to be generally satisfactory with respect to its ability to operate in the presence of enemy jamming. A new video amplifier was built and found to be 15-20 db less susceptible to jamming than the amplifier in the radar system. The i-f amplifier was difficult to overload, a good AJ feature. The high-power magnetron and high-gain antenna array tend to make effective jamming difficult. The AFC is a useful AJ measure except when the jamming is strong enough to take control. Reducing the receiver gain reduced the vulnerability by 5-10 db. The report includes photos of screen images, suggested AJ procedures, and circuit diagram for new video amplifier.

411-66 (P-100, RP-246) (H. C. Pollock). Airborne jamming operations against EW and GCI radars and v-h-f communications at Orlando,

SECRET

Florida. The equipment in each of three AT-18 planes comprised one B-2000 (against SCR-270), two B-2200 (against SCR-588), and one modified SCR-522 which was not strong enough to jam v-h-f communications satisfactorily. The results in jamming the radar systems, as detailed in the report, were eminently successful.

411-98 (Z-1800, RP-172) (J. H. Woodruff, A. Keck). Field tests of an airborne ASG radar jammed by a ship-borne L-105 transmitter indicate that the L-105 should be an effective source of jamming signals. Good radar operating techniques reduce jamming effectiveness by as much as two-thirds. The techniques include frequent adjustment of gain control in homing on a normal target and detuning the local oscillator for protection against narrow-band jamming, as well as the use of AJ devices.

411-146 (L-1500, RP-436) (F. P. Cowan, R. H. Hoglund, D. R. Scheuch). Reports on the extreme jamming vulnerability of Mark 31 radar-controlled missile. The receiving system is very susceptible to both modulated and unmodulated jamming, largely because of i-f overload aggravated by the action of the AVC circuit. A suggested AJ measure is that the i-f gain be reduced and the video gain be increased, thus making the receiver less susceptible to overload by continuous wave. The report includes a brief description of the Mark 31 and a discussion of the experimental procedure.

411-131 (E-2200, RP-355) (F. P. Cowan, R. H. Hoglund, D. R. Scheuch). Investigation of Navy *radar homing bomb* [RHB] shows that its electrical circuits are extremely vulnerable to c-w and modulated jamming, being made completely inoperative by a J/S ratio of less than 1 for continuous wave. No recommendations are made for AJ modifications. The device might be adapted for RCM use against Japanese 10-cm radar. The report describes RHB and includes block diagram, response curves, etc.

411-205 (E-3000, RP-452) (F. P. Cowan, K. A. Davis, J. H. Woodruff). Finds that the *jamming susceptibility of AN/APQ-5B* blind bombing attachment is somewhat greater than that of the SCR-717B radar from which it is operated. Performance is improved by using a short-time-constant coupling circuit, for which field installation instructions are given.

411-219 (E-3100, RP-453) (H. O. Anger). Finds that the *jamming susceptibility of AN/TPL-1* ground-based searchlight-pointing radar is of relatively slight degree, except for off-target jamming. The generally satisfactory performance is consistent with the AJ measures which have been built into the set. The direction of the jammer can be accurately found for all types of jamming except when the modulation is closely synchronized to the spinning rate of the radar dipole. A small amount of off-target jamming causes angular errors sufficient to throw the controlled searchlight off target.

411-214 (E-2600, RP-368) (J. W. Woodruff, F. P. Cowan). Reports on the *jamming susceptibility of AN/APG-1* autotracking, gun-laying radar. It also describes a field modification to eliminate a range-gate jitter which caused unsatisfactory operation of the set as originally received. The modified set was found to be more vulnerable than a nonautomatic radar, but less vulnerable than the automatic RHB and Mark 31.

411-215 (E-2800/E-2900, RP-449) (R. H. Hoglund). Reports on *the jamming susceptibility of AN/APS-4 radar and APA-16* bombing attachment. The APS-4 displayed extreme vulnerability which was decreased by adding a short-time-constant coupling circuit. The use of grid-voltage control of gain and modification of the AFC are recommended to improve the overload performance. The susceptibility of the APA-16 is the same as that of the APS-4, except that angular errors may occur during off-target jamming.

411-183 (E-2300, RP-367) (J. H. Woodruff). Reports on tests of *jamming susceptibility of SCR-720A* and finds that jamming does not greatly impair the effectiveness of this radar. Accurate homing on the jammer is possible at all ranges. It is estimated that a heavy bomber should show through jamming at about 1 mile. It is recommended that no further AJ modifications be made beyond the addition of manual r-f gain control as proposed by Aircraft Radio Laboratory.

411-231 (E-3300, RP-475) (J. H. Woodruff, H. O. Anger, K. A. Davis). Reports the results of laboratory and field tests of the *jamming susceptibility of SCR-545* fire-control radar using a 200-mc system to search and either put a 10-mc system on the target, if the 10-mc signals are strong, or automatically track in range and azimuth, if the 10-mc signals are weak. Jam-to-signal ratios of 16-33 db for continuous wave, 10-18 db for 100-kc sine wave, and 6-8 db for noise were found necessary to jam the microwave receiver. In the autotracking circuits, ratios of 0 db were found to destroy azimuth accuracy and about 5 db to destroy range tracking. The azimuth and elevation of the jammer could be accurately determined. The search receiver was found to be relatively unsusceptible if a fast time-constant coupling be added.

411-TM-56 (H. O. Anger). Discussion of AJ practice, description of, directions for installation, photos, and drawing of *plug-in AJ high-pass filter.*

Div. 15	RP-224	Navy	1.42 for CW55AAB
RRL	E-510		

This device protects against low-power continuous wave and low-frequency modulated jamming of Mark III, Mark IV, and SCR-296A radars by removing the modulation from the jamming signal. It consists of an octal adapter socket to break the grid lead to the last video amplifier tube, a pair of shielded leads to a toggle switch mounted on the front panel of the indicator unit, and a resistor and condenser constituting the filter and mounted on the switch; by interchanging two resistors a 2 μsec or a 4 μsec time constant becomes available. The unit can easily be installed by maintenance personnel. In the hands of a well-trained operator it will not only accomplish its stated purpose but will also help slightly in reading through other types of modulated jamming signals.

411-IB-24. Description and directions for installation and operation, with photos and drawing of plug-in AJ high-pass filter (RP-171, E-1610). This device resembles E-510 in purpose and construction, except that it is used to improve the operation of SCR-268 and consequently has two octal sockets to open the grid leads to the two parallel tubes of the last video stage. It is designed for a time constant of 9 μsec.

411-118 (R. S. O'Brien, W. Y. Pan). Illustrated description of recommended changes in i-f circuits and reasons therefor, including summary of performance characteristics and preliminary instructions for installation of *detector video replacement units for SCR-268.*

Div. 15	RP-171	Army	BC1324 and
RRL	E-1601, E-1602		BC1325

The E-1601/E-1602 units are used together to achieve improved operation of the SCR-268 in the presence of certain types of jamming. These two units replace the E-1610 plug-in filter where that has been applied.

411-164 (W. Y. Pan). Recommends *changes in i-f circuit of SCR-268* to prevent serious reduction of receiver gain following the transmitter pulse. The change involves the use of self-bias instead of fixed bias in the last two i-f stages, thus avoiding common coupling. The improvement is shown by comparative oscillograms.

411-179 (W. Y. Pan, R. S. O'Brien). Summarizes various *AJ developments for SCR-268 radar systems.* These include the E-1610 plug-in high-pass filter and the E-1601, 1602, 1602A, 1605, 1606, and 1607 modification units.

Antijamming Video Filter Attachment.

Div. 15	RP-224	Army	BC-1375
RRL	E-515	Navy	CAOS-50 AEY

This attachment for Mark III, Mark IV, and SCR-296 radars helps to minimize the effects of certain types of jamming signals, as described in 411-TM-87. It consists of a linear diode detector, various high-pass and band-pass video filter sections, and a two-stage video amplifier. The various filters are switch-selectable to pass frequency components of desired pulses and to attenuate undesired modulation frequencies. The video amplifier allows considerable reduction in the receiver gain, thus delaying overload without losing pip amplitude.

411-TM-87 (H. O. Anger). Outlines method for protecting Mark IV against jammers modulated by high-frequency sine wave or narrow-band noise. The method involves slightly detuning the radar transmitter from the jammer to get a beat frequency between the two, and then using video filters to separate the beat frequency from the jammer modulation frequency (or also from the beat frequencies between barrage jammers). The memo includes circuit diagrams and typical oscillograms.

411-IB-56. Modifications and alterations for adapting unit so that it can be used with SCR-296 radar.

411-TM-117 (H. O. Anger, R. S. O'Brien). Discusses the principle and effectiveness of detuning, summarizes preliminary development work on radar AJ detuner (RP-224, E-512). This is an auxiliary tuning attachment to facilitate the AJ technique of detuning the receiver local oscillator. It is specifically designed for Mark III, Mark IV, and SCR-296A radars. Presents oscillograms illustrating how it helps in the case of continuous wave and modulation with 50 kc.

411-TM-51 (E-800, RP-214) (R. S. O'Brien). *Various AJ devices to be used with the Mark IV* FD radar. These include a delay line for widening the train scope gate, video gain control, high-pass video filter, back bias, and local oscillator tuning. These devices have been installed for subsequent laboratory and field tests.

411-IB-14. Illustrated description and preliminary instructions for installation and operation of plug-in AJ high-pass filter (RP-224, E410). This video filter coupling circuit improves the operation of the ASB series of radar receivers in the presence of jamming. It consists of an RC circuit mounted on

SECRET

a special switch connected to two socket adapters to be inserted in place of the detector and first video tube, which are plugged into sockets on the tops of the adapters. The report includes photos of images of c-w jamming, sine wave-modulated jamming, noise jamming, and sea clutter, with filter off and on.

411-178 (E-400, RP-223) (R. E. Kell). Summarizes the results of theoretical and test investigations of the *jamming susceptibility of ASB* radar systems, and suggests various AJ measures. Jam-to-signal ratios of 9.6 db (for continuous wave) and 2.4 db (for 10 kc sine wave-modulated continuous wave) were found to jam a typical receiver completely. These ratios were improved by 8 db and 15 db respectively after inserting E-410 high-pass filter. The receiver's overload level was increased 10 db by the E-412 modification of the last i-f stage. The system frequency can be shifted from that of the jamming frequency by the E-409 remote tuning unit for ASB-6 and ASB-7A and by the E-413 for the ASB-7B. The E-411 gang tuning mechanism, when used with E-409, provides simultaneous control of the transmitter and receiver frequencies, thus giving single-control tuning for the system. These various AJ devices are fully described in the report, with photos, curves, and performance data on the improvements they effect.

411-TM-33 (L-900, RP-277) (J. H. Woodruff). *Two new antijam video amplifiers for the SCR-717B.* One involves a production line change and the other indicates changes which can be made in the field. With the present amplifier, noise jamming need be only 1 db stronger than the echo to obscure it, whereas with the new amplifier the ratio is 16 db. The new features are an optional short-time-constant coupling circuit and the use of a pentode instead of a triode limiter. The report includes circuit diagrams and detailed discussion for both amplifiers.

411-46 (RP-277, L-901) (J. H. Woodruff). *The AJ video amplifier for SCR-717B.* This unit is designed to replace the video amplifier in the SCR-717B radar equipment. The new unit minimizes the effect of certain types of jamming and sea echoes and, under normal operating conditions, provides a better video picture on the scope. Its higher overall gain permits decrease in i-f gain with consequent increase in jamming power necessary for i-f saturation. The use of a sharp-cutoff pentode instead of a triode limiter minimizes overload and base line displacement. The h-f response extends to 5 mc instead of to 1 mc. The unit uses the same mounting holes as the original and is easily installed. It employs two optional short-time-constant video couplings. Results of field jamming and laboratory tests show that the replacement amplifier not only reduces the vulnerability to jamming by 15-25 db, but also gives an improvement over the original in normal operation.

Range Indicator for Navy Mark IV Radar with Window.

Div. 15 RP-406
RRL E-2106

This attachment aids in determining the range of moving targets that would ordinarily be lost in Window or ground clutter. The obscured targets are located by searching in range until characteristic audio doppler or propeller modulation is heard in headphones. After gating a very small section of the range, the modulation of any echo in this gate is presented to the range operator through headphones. Since the width of the gate is less than a pulse length, the approximate range of a given target is obtained by adjusting the range control to maximize the doppler tone. The unit comprises a gate generator triggered by a pulse from the leading edge of the range notch, a stage for mixing the narrow gate and the video signal, a stage to amplify the gated video signal, and filters to remove the pulse repetition frequency [prf] and the lobing interference of the radar.

411-170 (H. O. Anger). Complete description and discussion of theory of operation, photos, schematic diagram, waveforms, and frequency-response curve.

411-274 (E-2103, RP-406) (E. R. Brill). Discusses several *limiter circuits for use with intensity-modulated indicators* in radar systems employed in tracking targets through clutter-infested areas or in the blind bombing of complex land targets. When such indicators are operated with conventional linear limiter circuit their dynamic range is insufficient to allow simultaneous presentation of very strong and very weak echoes without saturating uniformly on all signals above a certain rather low amplitude. The range can be greatly extended by using nonlinear circuits in the video amplifier to compensate for the cube-law transfer characteristic of a cathode-ray tube. One type of circuit employs two shunt diodes as the nonlinear elements and another type employs a crystal rectifier. The report recommends that these two types of signal-amplitude compression circuits be tested under operating conditions.

411-TM-25 (E-601, RP-213) (D. R. Scheuch). *Means for distinguishing real aircraft echoes from artificial echoes,* such as those due to Window.

SECRET

Toward this end are summarized the results of tests to detect the 50- to 160-c modulation caused by the rotation of the propellers. This a-f modulation could not be satisfactorily reproduced because the receiver of the Navy Mark IV was not sensitive enough and because of difficulty in filtering out unwanted frequency components in the echo output. Synthetic Giant Wurzburg, 565 mc (Adjustable 540-565 mc).

Div. 15 RP-179
RRL E-1100

Various modifications of an SCR-545A radar permitting partial simulation of a German Giant Wurzburg with a peak power of 5 kw (adjustable 3-15). The salient characteristics are as follows: prf 1750 per second, average pulse width 2.2 μsec, lobing rate 25 per second, antenna gain 875, lobe split 3 degrees, lobe width at half power, 3.3 degrees, maximum range 55,000 yd.

411-81 (F. P. Cowan). Describes new units and changes in old units with photos, circuit diagrams, and sketches of components.

411-81A (J. F. Youngblood, C. M. Daniell). Describes later modification of antenna to permit 90-degree elevation and 360-degree rotation.

411-77 (G-606, RP-318) (P. J. Sutro). *Photographic integration* or the use of a long-persistence screen is found theoretically to improve the visibility of a weak signal through noise on an A scope (deflection modulation). Either method overcomes the lack of homogeneity in the pattern that makes direct visual observation difficult. Short exposure photographs should bring out the contrast at the base line. For longer exposures the camera should be adjusted to emphasize the contrast at large deflections. The long-persistence screen would be used with an (added) intensity-modulated circuit to decrease the beam intensity at small deflections; the screen should be viewed through a filter to eliminate the "flash." An artificial overload in the receiver may help in distinguishing a weak signal.

411-84 (E-605, RP-318) (E. R. Brill). Discusses the use of *long-persistence* cathode-ray tubes versus photographic integration of pulses as a means for improving the readability of echoes through noise jamming of early-warning radars. It finds the long afterglow tube to be more practical for combat use.

411-39 (E-604, RP-213) (E. R. Brill, C. Gray, A. M. Hughes, O. G. Villard). Describes equipment and methods for still and cine-*photography of various types of oscilloscope patterns* observed in RCM and radar operations. Photographs and pertinent data of typical indications are included in the report.

411-TM-32 (E-605, RP-318) (E. R. Brill). Discusses the usefulness of *long-persistence screens* as a countermeasure against Window and concludes that the method is worth further investigation.

411-TM-124 (E-2000, RP-214) (F. P. Cowan). Illustrated description of experimental installation of SC indicator, OAV signal generator, and CG46ACG for AJ studies, and of a simple method of using these components for *AJ training.*

411-94 (Z-2500, RP-387) (F. P. Cowan). Discusses the RRL *training course* in defensive countermeasures for a selected group of Navy officers. The report explains the plan, gives the syllabus, and discusses the phases of the work at RRL and Fort Lauderdale.

411-110 (E-1400, RP-343) (D. R. Scheuch). Describes modifications of SCR-648 used in building a *synthetic Wurzburg* (both small and Giant) for testing RCM equipment. The installations are similar as regards type of antenna lobing, radio frequency, peak power, prf, and pulse length.

411-112 (E-608, RP-318) (E. R. Brill, F. P. Cowan). Discusses the combined use of *lobe switching for transmission* and a single stationary lobe for reception as an AJ method for ASB radars. A graphical and experimental analysis demonstrates that such an arrangement eliminates the scope clutter (undesirable l-f modulation of jamming signals) and the bearing error in the presence of off-target jamming that occur when lobe switching is used for reception. The training accuracy is about half that obtained with the usual method of lobing for both transmission and reception. The improvement is illustrated by photos of scope images. Possible applications of this technique, which requires more complicated antenna installations, are briefly discussed.

411-128 (G-202, RP-182) (D. Middleton, P. J. Sutro). Proposes the use of a differentiator circuit in the video stage of a radar receiver as an *AJ system against Chaff* (sown radially in the beam width). The purpose is to concentrate the target return so as to make it visible in the Window disturbance. The theory of operation, as discussed qualitatively and analyzed quantitatively, depends upon widening the i-f and video bandwidths sufficiently to enable successful operation of a modified receiver having Type A presentation. The conclusions are that (1) considerable improvement can thus be obtained for pulse lengths of 3 μsec or more, with little improvement for lengths of 1 μsec or less, (2) range decreases as pulse width is increased, due to mismatched i-f stages and thermal noise from the mixer, (3) a single differentiating circuit is more

SECRET

effective than multiple differentiation in the video amplifier, and (4) the method is applicable against narrow-band noise jamming when the noise spectrum is narrower than the i-f or video bands of the unmodified receiver. The method should be somewhat more effective against Ropes and Angels than against Chaff.

411-167 (E-2700, RP-447) (J. H. Woodruff). Reports favorable results of investigating an *AJ method for search receivers* that are subject to jamming from an associated spot-jamming transmitter. By feeding directly to the receiver a small portion of the transmitter output in proper amplitude and phase, the jamming picked up on the receiver antenna is canceled. The parts required comprise a line stretcher, two probes, and a cable, which may easily be added externally to any spot-jamming installation.

411-207 (E-609/L-1321, RP-214) (J. H. Woodruff, A. Keck, R. S. O'Brien). Discusses signal cancelation by crossed dipoles as an *AJ measure for elliptically polarized jamming*. The jamming signals are received on two separate crossed dipoles with outputs properly adjusted in amplitude and phase to balance out the signals and thus leave a radar echo essentially unaffected by jamming with any type of modulation. The correctness of the theory was satisfactorily verified experimentally, as shown by photos of scope images and by performance curves. Investigation of a similar technique for a radar with conical scan demonstrated that a fixed dipole in an auxiliary reflector gave cancelation at one point in the scan.

DECEPTION AND CONFUSION DEVICES

4.1 MECHANICAL DECEPTION AND CONFUSION DEVICES

Chaff.

Div. 15 RP-103 RRL G-500
Army AN/CHB, AN/CHA

Chaff consists of packaged narrow strips of aluminum foil designed to be so dispersed that their reflection of a radar beam simulates the echo produced by a large air or surface craft. The strips are machine-cut to a length corresponding to a half wavelength of the enemy frequency to be confused. Early types were paper-backed, and either flat or bent (to stiffen them). The latest type is made from embossed aluminum foil without paper backing; its dispersal properties are superior. All types are furnished in unit packages, each of which simulates the echo of one bomber. Later types are taped or strung together to facilitate machine dispensing of three units at a time. Specifications for AN/standard types are:

Description	Type No.	Freq. range (mc)	Length by width (inches)	Strips per package
Flat paper-backed	CHB-0	110-116	52x0.25	50
	CHB-05	86-230	60, 48, 38, 30x0.25	50, 100, 125, 150
	CHB-1	193-224	27x0.25	250
Bent paper-backed	CHA-2	347-404	15x0.08	1,000
	CHA-28	450-600	11½, 10x0.045	1,800, 1,800
	CHA-3	510-595	10$\frac{3}{16}$x0.045	2,000
	CHA-4	660-770	7$\frac{7}{8}$x0.045	3,000
	CHA-5	2,700-3,400	1$\frac{3}{16}$x0.045	30,000
	CHA-6	8,100-10,600	$\frac{19}{32}$x0.045	300,000
Bent embossed	CHA-2-(3)	335-390	15½x0.06	2,200
	CHA-25-(3)	320-600	15½, 12, 10x0.06	2,700, 2,700, 2,700
	CHA-28-(3)	450-600	11½, 10x0.06	3,000, 3,000
	CHA-3-(3)	520-600	10x0.06	3,600
Bent embossed in taped package	CHA-25-(3)T CHA-28-(3)T CHA-3-(3)T	Same specifications as for corresponding untaped type. Used with G-1107 double tape dispenser. One package is equivalent to three units.		

411-4 (A-400) (L. J. Chu). Derives *formulas for intensity of echo* from isolated sphere, disk, rectangle, cylinder, edge reflector, and corner reflector, and applies the results to the problem of producing a false echo at 10-, 53-, and 300-cm wavelengths. The formulas are derived in terms of an echo constant (k) which is equal to $(R/\lambda)^2$ times the ratio of the power density of the echo wave to that of the incident wave at a distance (R) of one wavelength (λ) from the reflector. A single corner reflector is

SECRET

found theoretically[a] to be superior for $\lambda = 10$ cm, and an aggregate of long narrow conductors (length approximately $\lambda/2$) for $\lambda = 53$ cm and $\lambda = 300$ cm.

411-50 (G-500) (F. L. Whipple, W. W. Farley). Summarizes preliminary investigations as to materials, sizes, amounts, packaging, and production methods for *a unit of Chaff to simulate the echo from a large bomber* at various frequencies in the range from 100 to 10,000 mc. A suitable material was found to be thin aluminum foil mounted on paper and made rigid by cutting and bending into long narrow strips. In the 350- to 1,000-mc range a 3-oz package of strips $\lambda/2$ in length and falling 2-4 mph was found to simulate one bomber during the period that the strips infested the area covered by the radar beam. Greater weight per unit and much smaller actual lengths were required for the 1,000- to 10,000-mc range. In the 100- to 350-mc range better protection for shorter periods was provided by straws[b] formed from the paper-backed foil. Conclusion was that a skilled radar operator should be able to distinguish Chaff echoes from those of aircraft. Report includes brief illustrated description of rotary cutter for quantity production of Chaff.

411-73 (G-1400, RP-257) (G. P. Kuiper). Gives graphs, photos, and interpretations of *field tests of the relative effectiveness of six types of paper-backed Chaff* at 515 mc for both vertical and horizontal polarizations. The chief conclusion is that echo fluctuations are governed by a Rayleigh distribution throughout a total range of 30 db, the rate depending upon the radio frequency and the rate of horizontal dispersal. The time of fall through 1,000 ft is 3 min for vertical polarization and 5 min for horizontal polarization. The report includes a determination of the main lobe of Yagi antennas and frequency curves of echo strengths. The general conclusion is that the random echo of large infestations of Chaff approximates echo of flight of planes.

411-TM-108 (J. Levine). Tabulates results of *field dispersal tests of CHA-3* in 15-in. and 6-in. wrappers. Average results were about 50 per cent dispersal (as compared to 85-100 per cent with embossed foil). Additional tests against a radar beam showed that echo strength is improved by increasing strip width.

411-91 (G-500) (G. P. Kuiper). Subsumes and interprets *information on Window* presented in previous reports and reaches a number of important conclusions, including the fact that embossed full-hard aluminum foil is better than paper-backed foil as a material for Chaff and Rope. The embossed foil does not "nest," has smaller weight and volume per effective unit, and saves paper, glue, and labor. It can be cut and bent by existing cutters slightly modified and is more effectively dispersed by dispensing machines. Its rate of fall is from 200 to 350 ft per minute. Among the facts not mentioned in preceding abstracts about Chaff is a simple formula for figuring strip length: $L = 56$ in./F, where F is the frequency in 100 mc for the principal resonance peak. Included curves show that there are also secondary peaks at integral multiples of the resonance frequency, with heights decreasing roughly as the square of the number of the overtone. These curves indicate that the bandwidth extends from -6 per cent to $+7$ per cent of the peak frequency and increases by a factor of 1.2 each time that the Chaff width is doubled. No Chaff is yet available for efficient jamming of microwave radar in vertical polarization, although a new product, CHA-45, may hold the clue to solving the problem, utilizing the second and third overtones of long strips falling in random orientation. The report includes a few remarks and examples on the tactical uses of Chaff and on anti-Chaff measures.

411-236 (F. L. Whipple, A. T. Goble, A. W. Tyler, M. Hamermesh). Comprehensively recapitulates the development and application of all types of mechanical deception and confusion devices, including Chaff, Rope, and Angels. The treatment is descriptive and historical and effectively replaces all previous reports. New subject matter includes the use of projectile Window (in bombs) to identify front lines and landing points, an explanation of the theory of Window, and an account of the operational uses of Window.

411-TM-127 (G-1800, RP-257) (F. Bloch, M. Hamermesh). Derives *equations for the return cross sections* from random-oriented Chaff.

411-TM-126 (G-1800, RP-257) (R. D. Sard). Computes the *response of microwave Chaff* for different polarizations and angles of elevation. With horizontal polarization the response is found to be sensibly independent of the angle of elevation. With vertical polarization the response is near zero from the horizon up to about 30-degree elevation and then rises rapidly toward a maximum value at 90 degrees. A system on vertical polarization is less vulnerable to Chaff, the advantage over horizontal polarization being 32.4 db at 10 degrees, 5 db at 50 degrees, and 0.6 db at 70-degree elevation. With rotating polarization the response varies as the plane of polarization is turned and also varies with changes in Chaff configuration and distribution.

a It is not yet verified experimentally that a corner reflector is superior to Chaff at any radar frequency.

b Now superseded by "Ropes"; see 411-91.

SECRET

411-106 (F. L. Whipple). Table of available types of Chaff and Rope with information as to polarization, frequency band, and weight for each type.

411-103 (G-1800, RP-406) (J. H. Van Vleck, F. Bloch, M. Hamermesh). Discusses mathematical theory of the *response of Chaff* as a function of its cross section, which, in turn, is found to depend upon the ratios of Chaff length ($2l$) to effective radius (a) and to radar wavelength (λ). The quantitative results of two independent solution procedures are presented in a series of graphs showing the mean cross section of randomly oriented Chaff and the effect of the angle of incidence on the cross section. The mean cross section assumes maximum values when $4l/\lambda$ is slightly less than the "resonant" integral values ($n = 1, 2$, etc.). If d denotes the ratio of returned to incident power, the value of d/λ^2 at resonance increases slowly with n, and decreases rapidly for nonresonant values of $4l/\lambda$, reaching minimum values near $3/2$, $5/2$, etc. These minimum values increase as $2l/a$ decreases. Also, the heights of the minima increase and approach the height of the resonance peaks as $4l/\lambda$ increases. The theoretical results are compared with preliminary experimental results.

411-125 (G-1800, RP-406) (R. Weinstock). Finds that the echo cross section of *square sheets of Chaff* is not satisfactory for use as short-wave Window, considering the weight-to-response ratio. The report also includes a theoretical evaluation of *broadside echos from circular cylinders,* for perpendicular polarization.

411-174 (G-1800, RP-406) (F. Bloch). Derives general formulas for calculating the weight of *Chaff needed to protect plane formations against projectiles controlled by radar fuzes* (such as mc 382) by causing the projectiles to explode before reaching the formation. As an example of the use of the general formulas, it is figured that 400 lb give 75 per cent probability and 880 lb give 95 per cent probability of explosion while flying through 2,000 ft of Chaff-infested air. This should be adequate to protect a formation over a front 1 mile wide and $\frac{1}{5}$ mile high during 1 min of flight at 200 mph.

411-199 (G-1151, RP-406) (D. A. Peterson). Expendable Chaff dispensers can be hung on the bomb racks of fighter aircraft to dispense Chaff or Rope from a high altitude in advance of bombers requiring protection from enemy gun-laying radars. The units are released after serving their purpose, thus freeing the fighter for more active duty. An inner container is loaded with 350-400 bundles which are ejected by aid of a motor-driven stripper, an air-intake scoop, and an ejection tunnel. Report describes and gives results of flight tests of G-1151 mounted on P-51 aircraft. At 210 and 240 mph, RR 6/U Chaff was dispensed with better than 95 per cent dispersal, RR 4/U Chaff gave 75 per cent dispersal, and RR 3/U Rope appeared to be about 80 per cent effective.

Rope.

Div. 15	RP-257	Army	AN/CHR-1 & CHR-1T
RRL	G-1200, G-1800	Navy	AN/CHR-1 & CHR-1T

Rope consists of a roll of ribbon-shaped aluminum foil, 400 ft long and $\frac{1}{2}$ in. wide, and a small parachute (for vertical polarization), or 3-in. square card (for horizontal polarization). When assembled in packages of three rolls it is used to confuse radar systems operating at frequencies less than 500 mc. CHR-1T differs from CHR-1 only in that packages are taped for automatic dispensing by G-1107. Each package weighs 12.8 oz gross.

411-TM-28 (G-500) (E. Fubini, M. Hamermesh). Analyzes the use of metallized Rope as a substitute for Chaff. Theoretical conclusions indicate that Rope should be economically effective against EW but not against GCI and GL radar systems. For its weight to be comparable to that of Chaff, each Rope and parachute should weigh less than 1 oz.

411-TM-100 (G-1800) (F. Bloch, M. Hamermesh). Analyzes the effectiveness of Rope in producing vertically polarized radar echoes. The analysis is accomplished by aid of the Maxwell field equations and results in an equation for the cross section of the Rope in terms of the wavelength of the incident radiation and the length, width, and inclination of the Rope. The width is assumed to be large compared to the wavelength and the angle of inclination is assumed to be small.

411-TM-100A (G-1800) (F. Bloch, M. Phillips). Extends the result of TM-100 to cases where the wavelength (λ) of the incident radiation may be less than the width (d) of the Rope. Equations are derived for both vertical and horizontal polarization and the results of numerical computations are plotted in terms of cross section versus wavelength for the range from $\lambda = 314d$ to $\lambda = 0.314d$. It may be deduced from the curves that Rope is relatively ineffective for horizontal polarization at any λ/d ratio and for vertical polarization at ratios less than 3.14. Increasing the ratio to 31.4 multiplies the effectiveness by 3, and to 314 multiplies it by $12\frac{1}{2}$. In other words Rope is most effective for vertical polarization at long wavelengths.

411-91 (G-500). Reviews all phases of Window

(see Section 4.1 under "Rope"). It states that Rope gives 2.6 times the response at 100 mc than at 560 mc. Rope is found to be particularly useful when enemy frequencies are not known in advance or are widely scattered. The report includes oscillograms of a large number of Rope echoes in both vertical and horizontal polarization.

411-TM-125 (G-1800, RP-257) (F. Bloch, M. Hamermesh). Proves that the equations for the current distribution over a thin ribbon of width s and a thin cylindrical antenna having an equivalent radius a, are identical when a is replaced by $s/4$.

411-TM-133 (G-1200) (H. C. Pollock). Discusses the production of long lasting radar echoes from *balloon-supported Rope*. Rope is most effective for vertical polarization and for the frequency range from 50 to 200 mc. It may be carried at considerable speed toward enemy territory by upper air currents and appear as aircraft on an A scope. It can also be used to signal from an isolated position and to determine wind velocities at high altitudes.

411-TM-136 (G-1400, RP-406) (A. W. Tyler). Gives results of *field tests of Rope*, tuned and untuned. Mechanical tests showed that the rolls should be placed in individual cartons before they are packed in sleeves and that the opening shock at airspeeds up to 200 mph is absorbed by a 15-ft strip of cloth leader properly attached to the foil. Electrical tests indicated that three 400-ft rolls of foil give an echo equivalent to a head-on heavy bomber at 140 mc, with increasingly larger echoes at lower frequencies and with decreased amplitude at higher frequencies, dropping to the 3-db point at 500 mc. CHR-1, used against a vertically polarized system, has a useful life equivalent to a rate of fall of 5-6 mph. CHR-2 used against horizontal polarization has an effective rate of fall of 7-8 mph. The memorandum includes photos of packaged and opened Rope and of screen images for horizontal and vertical polarization at various frequencies.

Angels (G-1500, RP-258).

An Angel is a four-sided corner reflector having a radius of about 3 ft. It is designed to confuse microwave radars.

411-TM-91 (H. C. Pollock, J. Levine). Summarizes results of field tests in which the reflective power of an Angel was found to be proportional to the square of its linear dimensions, and, at 565 mc, to be equivalent to 0.1 the cross section of a heavy bomber.

411-TM-109 (H. C. Pollock). Summarizes results of field tests of the echo characteristics of two solid-foil and one mesh-foil balloon-supported Angels at 565 mc. The general conclusions were that the echoes fluctuate more violently than do those from an aircraft and that an increase in the size of an Angel causes a gain in echo size and range.

411-91 (G-500). Reviews all phases of Window (see "Rope" under Section 4.1). It explains that the use of Angels is necessarily restricted to the higher frequencies and that, until the enemy develops more microwave radars, the same Angel causes a much bigger echo in friendly microwave radars than in enemy radars.

411-TM-131 (G-1400, RP-158) (J. Levine). Summarizes results of field tests of *echoes from Angels* at 565 mc. Comparisons were made between 3- and 4-ft Angels, a 3-ft Angel and an AT-18, and both Angels and CHA-3 and an AT-11. In the size range considered the equivalent echo area of an Angel at 565 mc varies roughly as the square of the linear dimensions. The equivalent echo of a 3-ft Angel is one-eighth that of a B-17. A 4-ft Angel is the equivalent of an AT-11 or nearly one-fourth that of a B-17.

759-16 (RP-269) (G. Sinclair, R. B. Jacques). Briefly describes the method for measuring reflection patterns from a scale model and presents *reflection patterns* of Angel at 515 mc for vertical and horizontal polarization for various orientations in space corresponding to the manner in which Angels normally fall.

(February 14, 1944)

759-17 (RP-269) (R. B. Jacques). Presents *reflection patterns of Angel at 360 mc.*

(February 18, 1944)

759-18 (RP-269) (R. B. Jacques). Presents *reflection patterns of Angel at 410 mc.*

(February 20, 1944)

759-19 (RP-269) (R. B. Jacques). Presents *reflection patterns of Angel at 1,000 mc.*

(February 18, 1944)

759-25 (RP-269) (G. Sinclair, R. B. Jacques). Gives *results of reflection measurements on wire grids and mesh Angels at 2,000 and 3,000 mc.* A derived formula for calculating the reflection from wire grids is practically confirmed by the measurements, which seem to show that the reflection is independent of the polarization. Because large mesh sizes are found to be practically transparent to waves of a frequency at which small mesh is opaque, it is concluded that mesh is effective in the construction of a frequency-selective reflecting device. Corner action seems to become poorer as the mesh becomes larger.

(August 16, 1944)

SECRET

931-1 (H. C. Pollock, F. L. Whipple). A special report on *field tests of Window* against SCR-268 and SCR-270 at Florosa Field and against two 584 systems and a laboratory model XTIA at Camp Davis. The latter tests are considered quite favorable as regards the use of Window.

(July 6, 1943)

931-4 (RP-258) (W. K. Kearsley). Tells of experiments in developing *Angel corner folding reflectors,* 6-ft structures weighing less than 1 lb and launchable from a plane through a 5-in. opening.

(September 7, 1943)

931-27 (RP-258) (W. K. Kearsley). Describes the *construction of Angel corner reflectors.* The reflecting surfaces are of aluminum foil; the four arms of the frame are of bass wood; the central vertical member is paper shellac tubing.

(September 26, 1945)

4.2 ELECTRICAL DECEPTION AND CONFUSION DEVICES

411-102 (RP-210, D1400) (J. P. Woods, R. O. Petrich). *"Stardust" pulse repeater, 520-570 mc,* consists of a five-stage u-h-f tunable amplifier that is used to amplify and retransmit received pulses without distorting their shape, thereby causing a small target to appear to be very large. The repeater transmits a 20-mc bandwidth with a power output of 5 w for continuous wave or of 15 w for pulsed signals.

895-9 (RP-252) (H. O. Peterson, W. H. Bliss). Briefly describes three proposed *DF deception systems* to provide ship security during ship-to-ship and ship-to-shore communication. The systems are (1) meaconing, (2) noise masking, and (3) flash telegraphy, with (2) and (3) under consideration as the more promising, provided that a speed of 200-400 words per minute is adequate for (3).

(October 3, 1945)

895-40 (RP-252) (H. O. Peterson, W. H. Bliss, G. S. Wickizer, G. L. Usselman). Describes the *Blanket masking signal system* to obviate the need for maintenance of radio silence by a ship at sea in order to prevent DF detection of its position. The masking signal transmitted from a 5- to 15-kw land-based station is a noise-modulated carrier which is broken at a regular rate by short gaps of no radiation. On the same carrier frequency the ship transmits pulses at the gap rate, properly phased to arrive at the land-based station during the gap intervals when the ship signals can be received. At all points beyond and to the sides of the ship the two signals are so mixed that the ship signal is concealed. Results of two extensive tests indicate that further development is required in order to provide reliable communication over a 500- to 2,000-k range spread over a 180-degree sector about the masking station.

(October 3, 1945)

931-2 (RP-156) (S. Hansen, H. H. Race). Describes *field tests of Peter* installed on a 75-ft boat in Chesapeake Bay and employed to confuse an ASB operator on a PBY-5 trying to home on the boat. The tests indicated that Peter gives real protection to small boats and submarines from airborne radar-controlled night attacks. (Peter is essentially a wide-band r-f amplifier and modulator designed to receive and amplify pulsed enemy radar signals and modulate the return signal so as to deceive or confuse an enemy radar operator and prevent his obtaining a true bearing indication for gunfire control.)

(August 24, 1943)

931-3 (RP-156) (S. Hansen, H. H. Race). Gives results of *flight tests of Peter* against FD equipment at RRL. Fully automatic operation (with no indication that normal echoes were being modified) was realized up to 5 miles horizontal range at 5,000-ft elevation.

(September 22, 1943)

931-8 (RP-156) (S. Hansen). Presents the theoretical considerations involved in the design of a *multichannel amplifier with grounded grids* for covering a 20-mc bandwidth, such as is required for Peter.

(February 10, 1944)

931-10 (RP-156) (H. H. Race, S. Hansen). Gives results of *flight tests of Peter* equipped with two new types of modulators and working against a synthetic Giant Wurzburg (rotating polarization). Type E, which generates a sine wave automatically synchronized and manually phased with the radar lobing rate, produces a fixed error of 1.6 degrees or 38 per cent of the total beamwidth. Type F, which generates a random wave containing components uniformly distributed in a narrow band bracketing the radar lobing rate, produced in the radar bearing an uncertainty zone of 1 degree or 24 per cent of the total beamwidth.

(July 14, 1944)

931-25 (RP-156) (S. Hansen). A comprehensive exposition of the purpose, design, construction, and operation of *Peter.* Experience indicates satisfactory technical performance in rendering GL radars

SECRET

ineffective. Tactical requirements are found to be better met by jammers except for unusual cases such as proximity fuze countermeasure.

(November 16, 1945)

966-54 (RP-422) (K. L. Maurer). Discusses the effectiveness of various types of *countermeasures against Japanese high-frequency DF systems* and suggests equipment suitable for this application. A jammer equipped for automatic tracking is thought to be more effective than a meacon (a device which receives and rebroadcasts DF transmission at the original frequency, thereby causing an erroneous bearing at the DF station, since the field is the resultant of the original and rebroadcast fields).

(July 7, 1945)

966-55 (RP-422) (K. L. Maurer). Surveys the basic technical considerations that govern *countermeasures against radio-navigation aids.* General principles, including discussion of wave propagation, various antennas, direction finding, and range finding, are reviewed. Jamming and meaconing are described for various applications. Brief mention is made of methods for anti-countermeasure.

(October 15, 1945)

1045-MR-6 (RP-995) (D. K. Reynolds). Discusses the design construction and operation of a proposed *communications deception device, Elmer,* designed to provide automatic operation of one transmitter so as to simulate a net of several transmitters having different output powers and frequencies. It may be used with SCR-284, SCR-193, and/or SCR-506, in conjunction with a magnetic wire recorder containing information which automatically turns them on or off and keys them in accordance with the originally recorded signals.

(May 15, 1945)

1305-4 (RP-384) (O. H. Schmitt). Analyzes the *control mechanism of German BIVb tank,* which is loaded with an explosive charge and remotely directed by radio. The mechanism consists of a receiver and audio filter unit; a master-control, power-supply, and junction-box unit; a decoding unit; a detonation sequencing unit; a gear shift sequencing unit, and a hydraulic control unit. Each of these is illustrated and described.

(January 10, 1945)

1305-12 (RP-334) (J. Mead). Describes and gives the results of a-m *jamming tests of fm radio altimeters.* About 300 w of jamming power will cause a German FUG-101 to indicate too low an altitude, whereas 50 kw might conceivably be necessary to jam AN/ARN-1 and AN/APN-1 if used as proximity detonators. Because of the lack of a balanced detector, the German instrument is more vulnerable than the two American types. The report describes the characteristics of these three types of instruments and discusses possible power requirements in tactical situations.

(April 30, 1945)

1458-1 (RP-445). Recommends a field test program for *deception of the Japanese h-f* DF system in the 2- to 20-mc band. This DF equipment is of the elevated H type with crossed antenna and with receiver installed between the four fixed dipoles. The operator at the receiver position takes bearings with a hand-operated goniometer having an aural null. The proposal calls for the investigation of the polarization of sky waves and the development of a meaconing transmitter provided with frequency scanning and monitoring means.

(June 12, 1945)

TEST AND TRAINING EQUIPMENT

5.1 SIGNAL GENERATORS

411-TM-971 Test oscillator, 40-3,000 mc (A. Peterson).

Div. 15	RP-195	Army	TS-47/APR
RRL	U-500	Navy	TS-47/APR
General Radio	P-523A		

This compact instrument is used for testing and tracking receivers operating in its frequency range, such as AN/APQ-1, AN/APR-2, /APR-4, or /APR-5. It is calibrated for the fundamental 40- to 500-mc range in two bands (40-115 and 115-500 mc), and has usable harmonics up to 3,000 mc. The signals can optionally be unmodulated or modulated with 1,000 c at approximately 50 per cent or with pulses (70 μsec with pulse-repetition frequency [prf] of 500 c). It consists of a variable-frequency oscillator and a modulator, with an internal a-c or external battery d-c power supply. Modulation is provided by an audio oscillator which may be connected as a blocking oscillator to produce pulses. It is equipped with a built-in adjustable antenna or may be coupled directly to a receiver.

Pulsed Oscillator, 2,500-3,500 mc.

Div. 15	RP-292	Army	TS-82/AP
RRL	A-2651Y	Navy	TS-82/AP

This portable instrument was designed for field or laboratory checking of AN/APR-5 or /APR-6 performance in the 3,000- to 3,100-mc range. It

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consists of a 707B velocity-modulated tube in a cavity-type resonant circuit, a multivibrator pulsing circuit to put the tube alternately in an oscillating and nonoscillating condition, a power-supply circuit, a small antenna inductively coupled to one side of the resonant cavity, and a crystal detector loop-coupled to the other side to serve as a monitor. The resulting modulation is a pulse about 100 μsec in length with a prf of about 1,000 c.

411-TM-4 (J. H. Eldredge, R. B. Holt). Tentative specifications.

411-TM-112 (R. C. Raymond). Brief description and circuit diagram.

411-TM-8 Test transmitter. (RP-147, A-741) (R. B. Barnas). This portable instrument for checking the operation of a search receiver consists of an oscillator-modulator unit, a collapsible antenna, and battery box (or power unit). It normally radiates a small amount of pulse-modulated r-f power at the carrier frequency for which it is constructed. It supplies a continuous-wave [c-w] signal when the modulator tube is removed.

411-TM-9 Test buzzer. (RP-147, A2107) (H. T. O'Neill). This portable battery-operated instrument was used to check the operation of A-2100 radar warning receiver. It radiates a small amount of r-f energy which can be electrically coupled to the antenna rod or magnetically to the interconnecting cables by holding it close to either.

411-TM-94 Audio oscillator. (U-202, RP-315) (J. H. Jasberg). Outlines modifications of the Model B Hewlett-Packard *audio oscillator* to adapt it for satisfactory use with the AN/APA-6 pulse analyzer. The changes include the substitution of a precision dial to provide more accurate prf readings, the addition of high-impedance output terminals to provide sufficient output voltage to drive the sweep of the AN/APA-6, and modification of a standard cradle to permit the instrument to be mounted in a standard rack. Each change is shown by a circuit or constructional drawing.

411-TM-12. Carpet tester, 460-600 mc. (J. N. Dyer).

Div. 15	RP-289	Army	TS-52/APQ-1
RRL	F-2200	Navy	TS-52/APQ-1

This is a pulsed oscillator or miniature radar transmitter for field or shop checking of the locking action of AN/APQ-1. The pulses have a width of 2 μsec and a prf rate of 1,500-3,000. The signal is transmitted either from a dipole antenna mounted on the unit or through 20 ft of lossy cable.

411-TM-5. Wide-band r-f sweep generator, 100-1,000 mc (C. B. Clark, J. P. Woods).

Div. 15	RP-110	Army	AN-APQ-8
RRL	D-1308	Navy	AN-APQ-8

This device is used to determine the frequency response of r-f amplifiers, mixers, and filters by showing the response curve of the unit under test on the screen of an external cathode-ray tube. It eliminates the need of a signal generator for frequency calibration. It operates by changing the frequency of an r-f oscillator in synchronism with the horizontal displacement of the spot on a scope. The oscillator output is impressed upon the device under test. The rectified r-f output voltage of the device is applied to the vertical deflection plates of the scope so that the vertical displacement of the spot is proportional to the amplitude of the r-f signal. A beat-frequency oscillator circuit is employed using the outputs of two 3-cm reflex klystrons fed into a common wave guide and mixed in a crystal mixer. The center frequency of a desired bandwidth is changed by adjusting the cavity tuning on the klystrons. Frequency modulation of the mixer output is obtained by modulating the reflectors of the klystrons with a 60-c sawtooth voltage obtained from the amplified output of a relaxation oscillator which also supplies a constant-amplitude sweep voltage for the scope. The sweep width is adjustable from zero to 100 mc by changing the amplitude of the 60-c sawtooth wave. The device is calibrated by means of an external wavemeter. An AVC circuit provides a nearly constant output voltage with change in frequency.

IB-78 (RP-306, U-800). Preliminary description of the installation, operation, adjustment, and maintenance of test oscillator, 1,500-3,500 mc. This calibrated signal generator is designed for general use with micro-wave receivers, filters, lines, etc. Single-dial calibrated control provides continuous variation in r-f frequency. More accurate frequency measurements may be made from a calibration chart and Veedor counter on the panel. Provision is made for panel adjustment of voltage necessary for optimum oscillation and for panel control of character of uncalibrated output, whether continuous or modulated. A bolometer and attenuator must be added if accurate measurement of output magnitude be required. The oscillator consists of a calibrated plunger-tunable cavity with either a 2K28 or 707-B reflex klystron. Pulsing is accomplished by varying the cathode or reflector voltage with a pulse obtained from a 6V6 in a blocking oscillator circuit. The prf ranges from 270 to 10,000 c with resulting non-adjustable pulse widths ranging from approximately 5 to 40 μsec.

411-277 (RP-473, U-1500) (W. B. Wholey). Describes the circuits for the U-1500 pulser, power supply, and proposed output attenuating and calibrating system. This field instrument employs a 2K28 tube as an oscillator to cover the specified frequency range in one band and to provide an output of 200 μw or more. The modulation is either c-w or ½- to 10-μsec pulses with prf of 45-4,000 c. The project was transferred to a manufacturer before completion at Radio Research Laboratory [RRL].

411-256 (E-3200, RP-221) (R. E. Kell). Describes an experimental model of the *X-band test jammer* to be used in determining the vulnerability of AN/APS-4. (See Section 7.2.) The transmitter consists of an experimental A-131 magnetron oscillator tunable in the 8,830- to 10,340-mc range with 50- to 100-w output and the modulator-power supply units of a modified AN/APT-4. Auxiliary items include an E-1800 modulation signal generator, spectrum analyzer, thermistor bridge, and 50-db directional coupler. The text informs on the design, development, and operation of the system, with block and circuit diagrams.

867-2 (RP-241) (P. S. Hendricks). Describes an interim *pulsed signal generator* for testing RCM receivers with a signal similar to that from a radar. An r-f oscillator (WE 368AS or 703A tube with parallel-line circuit arranged in a circle) with 180- to 850-mc range is modulated by means of a pulse generator (multivibrator) having 50- to 12,000-c range and 1- to 30-μsec pulse widths. The oscillator output is fed to an antenna where the signal amplitude and pulse shape are shown on a calibrated oscilloscope. The distance between the antenna and the receiver under test gives a comparative indication of the signal strength at the receiver.

(July 2, 1943)

867-3 (RP-241) (P. S. Hendricks). Describes the *CBS 166 pulse generator* for testing amplifiers and associated equipment which must pass pulse signals having a steep wavefront. The generator is also applicable to modulating low-power r-f oscillators or amplifiers for test purposes. The frequency range is 50-12,000 c with 1- to 30-μsec pulse widths and 150-v maximum output level across 1,000 ohms. The report includes circuit diagram and constructional drawings.

(August 5, 1943)

923-1 (RP-270) (D. B. Sinclair, R. A. Soderman). Gives *operating instructions for P523-A* oscillator for testing receivers in the field.

(December 7, 1943)

923-3 (RP-160) (A. P. G. Peterson). Gives *operating instructions for P525-A* signal generator for 90-250 mc (AN/TPQ-T2).

(June 5, 1944)

5.2 SPECTRUM ANALYZERS

Panoramic Spectrum Analyzer, 80-1,000 mc.

Div. 15	RP-175	Army	TS-54/AP
RRL	D-1203	Navy	TS-54/AP

This portable instrument for measuring the strength and frequency spread of signals is used to adjust a radar jamming transmitter on the ground. It analyzes a bandwidth of either 20 or 5 mc centered at any desired frequency in its range. It may be operated either with automatic sweep to show the spectral voltage distribution on the screen of a cathode-ray tube or with manual tuning for meter measurement of the relative energy in any 100-kc portion of the spectrum. The device is essentially a superheterodyne receiver with an untuned crystal mixer, local oscillator, and wide-band i-f amplifier followed by a sweeping local oscillator (either 5 or 20 mc), and a second narrow-band (50 kc) video amplifier. For panoramic presentation the sweeping oscillator is motor-driven and the output of the video amplifier is applied to the deflecting plates of the cathode-ray tube, which is swept in synchronism with the tuning condenser of the sweeping oscillator. For meter indication the sweep oscillator is manually tuned and output of the video amplifier is measured by aid of a calibrated bolometer.

411-TM-6 (W. B. Caufield). Specifications.

411-TM-6A (W. B. Caufield). Supersedes TM-6 and covers the characteristics, applications, technical features, and specifications of the instrument.

411-25 (W. B. Caufield). Operating principles and procedures, specifications, circuit diagram, and performance curve.

411-IB-39A. Illustrated description and preliminary instructions for installation, operation, and maintenance of RRL production model—block and wiring diagrams, characteristic curves, diagrams of conversion and functional waveforms, and photos of various transmitter spectra observed on analyzer.

411-292 (J. C. Riley). Suggests several precautions and techniques for quantitative measurements of noise spectra of transmitters, particularly those operating at frequencies beyond the normal range of D-1203. Such measurements may be made with tunable cavities known as echo boxes.

411-96 (RP-176, H-100) (G. P. McCouch, P. S. Jastram). Video spectrum analyzer, 100 kc—9 mc. This noise spectrum analyzer measures the energy in either an 11-kc or 33-kc band anywhere in the spectrum and, by means of an auxiliary cathode-ray oscilloscope, presents a panoramic view of the spectrum from 1 to 5 mc. At maximum sensitivity the analyzer will measure a noise input level of 3.5 $\mu v/kc^{\frac{1}{2}}$ (100-ohm input) or $10/\mu v/kc^{\frac{1}{2}}$ (50,000-ohm input) with gain constant to within 1 db over the range from 100 kc to 9 mc. The actual sensitivity is controlled by means of two calibrated attenuators fed through a cathode-follower input and preceding a 9.5-mc low-pass filter. The instrument is essentially a wide-range receiver operating on the superheterodyne principle with the intermediate frequency above the region of the spectrum to be investigated. The audio output indicator is a thermistor bolometer bridge. A regulated power supply is incorporated in the unit. The analyzer will detect peaks but will not detect narrow holes in the noise spectrum.

411-154 (RP-306, H-600) (P. S. Jastram). Low-frequency spectrum analyzer, 500 c-200 kc. This instrument accurately measures the rms value of components of the noise spectra in a 60-c pass band located anywhere within the rated frequency range. It operates on the standard heterodyne principle and measures noise levels as low as $100\mu v/kc^{\frac{1}{2}}$. The instrument comprises an attenuator, a high-pass filter, one stage of signal preamplification, a modulator and local oscillator, a low-pass filter and l-f amplifier, and a rectifier and voltmeter, with voltage-regulated power supply. No indication of waveform is given.

931-9 (RP-347) (J. H. Rubel, T. Hudspeth, R. E. Troell). Describes a *spectrum analyzer for the 100- to 1,500-mc range* of carrier frequencies showing spectra up to 70 mc in width. Radio-frequency signals above 250 μv may be analyzed from panoramic presentation on a 5-in. cathode-ray tube. The device is essentially a narrow-band superheterodyne receiver whose local oscillator is frequency-modulated with a 60-c sweep.

(March 18, 1944)

931-11 (RP-347) (E. S. Miller, J. H. Rubel). Instructs on *operation of RP-347 spectrum analyzer* in producing plot of relative signal amplitude versus frequency on cathode-ray tube screen.

(August 23, 1944)

931-15 (RP-392) (J. Kahnke, E. Taft, R. L. Watters, L. Apker). Describes a double superheterodyne type of *spectrum analyzer for the 10- to 3,500-mc range* showing spectra up to 200 kc in width. The instrument is tuned over the entire range by a single dial, has a 30-db rejection of spurious responses, gives a signal-to-noise ratio of 2 with a 100-μv signal in a 50-ohm line and, by means of a 115-mc logarithmic amplifier, presents a constant 30-mc portion of the band on a 5-in. cathode-ray tube. The amplifier handles a 35-db power range. Signals feed directly into a crystal mixer, a cascade combination of an input crystal, a filter network, and an output crystal. Frequency calibration accurate to within ± 5 mc from 500 to 3,500 mc is furnished by a spark-excited wavemeter. The 10- to 3,500-mc range is covered by using a Z668 tuned to 22,000 mc as the first local oscillator and a 2K33 tunable from 22,010 to 25,500 mc as the second local oscillator.

(February 1, 1945)

931-16 (RP-392) (L. Apker). Analyzes mathematically the conversion loss due to *reciprocity failure in crystal mixers.*

(March 9, 1945)

931-17 (RP-392) (L. Apker, E. Taft, J. Dickey). Describes the *double crystal mixer* used in the 10- to 3,500-mc spectrum analyzer and determines its behavior in terms of linear network theory with matrix equations. Solution of a numerical example for a typical silicon crystal satisfying the reciprocity condition shows a conversion loss of 23 db for double mixing. Most silicon crystals are found to satisfy the reciprocity condition, whereas some germanium crystals do not.

(April 2, 1945)

931-19 (RP-392) (E. Taft, J. Kahnke, R. L. Watters, L. Apker). Describes a double superheterodyne type of *spectrum analyzer for the 10- to 1,200-mc band* showing spectra up to 200 kc in width. This instrument uses the same principles and some of the same components as listed in 931-15. The characteristics of the two instruments are quite similar.

(August 3, 1945)

931-20 (RP-392) (J. Dickey, L. Apker). Derives a formula for conversion loss and gives results of measurements showing the *unreliability of the reciprocity theorem for welded germanium crystals.*

(September 28, 1945)

931-26 (RP-392) (R. L. Watters). Describes a variable-impedance *input circuit for 115-mc i-f amplifier* having 200-kc bandwidth. The circuit is designed for use in the spectrum analyzer described in 931-34. The practical range of the variable impedance is about 100-2,000 ohms.

(November 8, 1945)

931-34 (RP-392) (E. Taft, J. Kahnke, R. L.

Watters, L. Apker). Describes *spectrum analyzer RP-392K* designed to take the place of the analyzers described in 931-15, -19. The instrument employs type 1462 tubes (revised type 2K50) to cover the 10- to 3,000-mc range with a single control. Otherwise it is quite similar to those it supersedes. All spurious responses are suppressed by at least 35 db; approximately 100 mc of the spectrum is presented at any one time; frequency calibration is accomplished with a K-band wavemeter.

(November 8, 1945)

1045-MR-13 (C. B. Clark). Describes *modification of AN/APA-11 pulse analyzer* to facilitate prf measurements. This is accomplished by "opening" the sine-wave time base into an ellipse, thus permitting the base of the pulse to be seen without interference from the return trace. The report gives circuit changes necessary to provide the elliptical time base.

(May 25, 1945)

5.3 FREQUENCY METERS

411-TM-10 (J. F. Byrne). Frequency meter for pretuning AN/APT-3, 70-145 mc.

Div. 15	RP-294	Army	BC-1255A
RRL	B-2700	Navy	BC-1255A

This portable battery-operated frequency meter consists of a local oscillator-mixer tube, two-stage audio amplifier, and jacks for headphones or meter. A signal picked up on a short-wire antenna is mixed with the output of the local oscillator tuned to a frequency in the 70- to 145-mc range. The amplified beat frequency is applied to a test meter or headphones to indicate its presence. When the local frequency is identical with that of the signal, the beat frequency is zero and the meter dips or the phones indicate no signal. The frequency is read to an accuracy within ± 0.3 mc on a calibrated dial.

411-289 (C. D. Jeffries). Heterodyne frequency meter, 55-100 mc, 100-250 mc.

Div. 15	RP-245	Army	TS-99/AP
RRL	U/B-3000	Navy	TS-99/AP

This portable a-c operated instrument was originally designed for pretuning AN/APT-1 in the 60- to 225-mc range in a manner similar to that employed with B-2700. It was later modified to permit field measurement of frequencies in the 100- to 250-mc range by utilizing the harmonics of the local oscillator and of the received signal. It consists of a calibrated variable-frequency local oscillator (55-105 mc and 100-250 mc in a butterfly circuit) coupled to a diode mixer whose output feeds an audio amplifier; it also contains a built-in power unit. The energy of the frequency to be measured is coupled into the mixer, and the frequency of the local oscillator is varied until an audible beat note is heard in headphones connected to the audio amplifier. The audible beats indicate that the difference between the two frequencies is practically zero. Because of the many possible beat-frequency combinations it is necessary to locate two successive dial positions where beats occur, and then to determine the unknown frequency within an accuracy of about 0.25 per cent by the usual harmonic number technique.

411-TM-52 (L. A. Mayberry). Bandwidth adjustment indicator, 0.5 to 7.0 mc.

Div. 15	RP-293	Army	TS-92/AP
RRL	U/B-3100Y	Navy	TS-92/AP

This device provides a simple means for aligning broad-band (0.5-7 mc) amplifiers in the field. It may be used to align the i-f amplifier of a receiver (such as SCR-587, APR-1, or APR-4), the noise amplifier of B-2200, or the Dina 100-w power amplifier combination. The unit consists of a crystal mixer, low-pass filter, oscillator-mixer, two-stage i-f amplifier, peak rectifier, d-c amplifier, and indicating meter. The general procedure is to tune the subject amplifier (being aligned) to approximately the desired operating frequency, feed its output to the indicator (tuned to a frequency corresponding to the desired bandwidth), and adjust the tuning and mutual coupling of the subject amplifier to indicate maximum output.

411-TM-95 (RP-293, Y-700) (L. A. Mayberry). Bandwidth adjustment indicator attachment, 0.5-7.0 mc. This simple device is similar to B-3100 in purpose and design except that it requires a suitable communications receiver as a selective amplifier in determining the bandwidth of a wide-band i-f amplifier. It comprises a crystal mixer, low-pass filter, and metering circuit consisting of a copper oxide rectifier and test milliammeter for an audio voltmeter circuit. Part of the output of the noise amplifier under test is fed to the crystal mixer to produce sum- and difference-frequency components. The mixer output is fed to a filter passing the 0.5- to 7-mc difference-frequency components. These are fed to a receiver having a 0.5- to 7-mc tuning range and bandwidth not exceeding 100 kc. The receiver is tuned to a frequency corresponding to the desired bandwidth and the amplifier under test is adjusted to give maximum meter reading.

411-IB-35 (RP-306, F-4000). Wavemeter, 200-450 mc and 400-700 mc, and 700-1,500 mc by harmonics. This wavemeter is a part of F-2300 and

F-3600 and is used in measuring wavelengths in the fundamental range from 0.43 to 1.5 m or with harmonics (at reduced sensitivity) down to 0.2 m. It is tuned by means of two coaxial units permanently mounted in a single cabinet with separate inputs and a switch to connect either unit to the output meter. The output is fed through a crystal detector to a 100-μa meter equipped with a shunt resistance connected through a switch to reduce the sensitivity. The meter has a reading error of approximately 0.6 mc per division and an absolute error of less than 0.25 per cent.

411-TM-27 (U-100, RP-327) (M. T. Lebenbaum). Suggests approved methods for setting the frequency of AN/APT-3, /APT-1, /APQ-2, and /APT-2, by means of receivers available November 9, 1944. The general conclusions are that for spot jamming the transmitter must be set during flight after preliminary approximate setting before take-off and that accurate frequency meters are desirable in setting for either spot or barrage jamming. Detailed *suggestions* are given *for tuning* each of the four types of *jammers* under consideration.

5.4 MISCELLANEOUS TEST EQUIPMENT

411-TM-18 (W. D. White). Transmitter output indicator, untuned.

Div. 15	RP-290	Army	CV-9/APT
RRL	F-2305, F-2308	Navy	CV-9/APT

This simple device is used in tuning u-h-f transmitters to proxide maximum output, as indicated by comparative strength of antenna current, or to monitor transmitter output during flight. It consists of a pickup unit, a control unit, and intervening shielded cable. The pickup unit consists of a 2-in. antenna mounted near the transmitting antenna, a crystal rectifier, and an r-f choke. The control unit is mounted near the transmitter and consists of a rheostat and a milliammeter jack. The rheostat is adjusted to provide readable meter indication and the transmitter is adjusted to provide maximum meter reading. F-2308 is a simpler and more easily mounted model of F-2305.

411-127 (E. A. Yunker). Short illustrated description of CV-9/APT transmitter output indicator.

411-127 (RP-290, F-2306) (E. A. Yunker). Carpet output indicator, 450-710 mc. F-2306 is a portable device used as a temporary expedient in tuning a Carpet transmitter feeding an AN-132A antenna. It is similar to F-2305 except that it is hooked on the antenna and picks up the signal through a small probe.

411-TM-39 (R. R. Rhiger, R. B. Monroe). Radio-frequency power indicator.

Div. 15	RP-306	Army	TS-118/AP
RRL	Z-1600	Navy	TS-118/AP

This device gives a comparative indication of the power output of an u-h-f transmitter having a d-c path through its output coupling circuit. It employs a thermocouple (copper-constantan) in series with the inner conductor of 200 ft of RG-38/U r-f cable across whose output (where no appreciable radio frequency exists) is connected a low-resistance milliammeter. The meter measures the direct current flowing through the line as a result of the emf generated by the thermocouple. Since this emf is a function of the r-f power, the device can be calibrated (with correction for skin effect) to show meter deflection versus power input.

411-TM-12 (J. N. Dyer). Carpet checker, 200-450 mc and 400-700 mc, by two-unit wavemeter.

Div. 15	RP-290	Army	TS-53/AP
RRL	F-2300, F-3600	Navy	TS-53/AP

This is a combined modulation monitor, indicator of relative power output, and frequency meter for field or shop checking of jamming transmitters. It consists of an untuned receiver, a peak-reading voltmeter, and two interchangeable coaxial frequency meters. The voltmeter is used with a crystal detector, alone or with frequency meter, to measure the voltage of a pulsed or modulated signal. The frequency meter has a reading error of approximately 0.6 mc per division and an absolute error of less than 0.25 per cent. For modulation monitoring and power output indication the equipment may be used as a receiver without the frequency meter; when so used it has a sensitivity of 25 mv for usable output.

867-8 (RP-261) (O. J. Sather). Describes an *u-h-f power meter* to provide a visual indication of relative output at frequencies up to 1,200 mc. The device also furnishes a nonreactive termination for a 50-ohm transmission line. The circuit is fundamentally that of a peak-reading meter for measuring the voltage across a concentric load resistor and is calibrated to read the average power dissipated. The resistor is cooled by a high-speed blower. The inner conductor of the transmission line is brought through the resistor and connected to the plate of a special u-h-f diode (see 867-3 in Section 6.1).

(April, 1944)

High-Frequency Calorimeter Wattmeter, 300-3,000 mc (RP-306, Z-172).

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This laboratory instrument measures modulated or unmodulated r-f power up to 300 w with an accuracy of 5 per cent or better. The readings are for average power over a period of at least 2 min. The input impedance can be matched to any coaxial line or other impedance by means of a double stub tuner. Radio-frequency energy from a 50-ohm line enters a standing-wave indicator and passes through the matching section into a calorimeter load through which a hydraulic system maintains a constant rate of water flow. The temperature rise of this water, as measured by a thermopile, is thus directly proportional to the power dissipated in the load. The standing-wave indicator, by aid of an auxiliary oscilloscope, shows the form of the standing wave in a short section of the incoming line, thus indicating the degree of match or mismatch between the line and the load. The matching section is then adjusted to provide the pattern corresponding to the matched condition. The indicator consists of an electrically short circular section of 50-ohm line slotted to receive a crystal probe mounted on a motor-driven flywheel. The resulting rectified voltage from the crystal probe depends upon the distribution of standing waves in the slotted line and is applied to the scope through slip rings and brushes. The calorimeter load consists of an 11-in 50-ohm coaxial line (shorted at the extreme end) with a brass outside and a hollow copper center conductor. The latter is water-cooled on the inside and covered with a layer of graphite particles held in place by a Pyrex tube on the outside. The hydraulic system provides a constant rate of water flow and a thorough mixing of the outlet water, whose temperature is measured by a hot-and-cold junction thermopile calibrated with a microammeter.

411-TM-70 (J. G. Stephenson, R. L. Henkel). Complete illustrated description of construction and operation.

411-121 (Q-1400, RP-306) (W. R. Rambo, S. W. Howe). Describes the design and construction of a quick-reading calorimeter type *water-load for measuring r-f power* of 1 kw and more in the 250- to 800-mc frequency range, with an estimated accuracy of within 10 per cent. The device comprises a 50-ohm input tapered matching section with crystal probe and microammeter for relative power indication, a power dissipator consisting of a shorted attenuating coaxial line with Cromax resistance wire as the inner conductor and water as the dielectric, a differential thermocouple and microammeter, and a circulating water system. The thermocouple measures the temperature rise in the circulating water, the meter being calibrated for various rates of regulated water flow. Reading time for absolute power measurement is 45 sec, and for relative power (from crystal probe) is instantaneous.

411-209 (Q-410, RP-169) (W. R. Rambo). Describes a small calorimeter type *r-f wattmeter for 1,000- to 3,000-mc range* with an accuracy estimated at ± 5 per cent. The instrument gives a direct reading of 0- to 50-w r-f power input. The power is dissipated in a 9-in. length of coaxial line filled with tap water. The low input impedance of this attenuating section is matched to 50 ohms in a 5-in. length of coaxial line of uniform conductor cross section having an exponentially tapered titanium dioxide dielectric. The instrument requires no tuning and can be read in 10-25 sec, depending upon the rate of water flow. An instantaneous indicator of relative power is also provided. The report includes photos and drawings to illustrate constructional suggestions.

411-246 (U-1200, RP-306) (C. F. Hadley). Describes a partly developed *microwave wattmeter* for measuring power in a transmission line in the 2,700-3,300-mc range. This laboratory instrument employs a directional coupler and a double thermistor bridge. It can be calibrated to give direct readings of incident and reflected power. The report opens with a discussion of why this type of measurement is more convenient than calorimetric or slotted section transmission line measurements. Complete drawings are given for the coupler, with a circuit diagram for the thermistor bridge. From experiments it is concluded that some work has yet to be done in eliminating an error present at high standing-wave ratios.

411-247 (Q-1900, RP-306) (L. A. Manning.) Describes a *self-calibrating thermistor bridge* for measuring r-f power in the range from 0 to 40 mw as read from a calibrated attenuator. The bridge operates on the principle of power substitution with a single balance control. An accuracy of better than 5 per cent is obtained, being independent of ambient temperature and thermistor characteristics.

411-280 (Z-1600, RP-409) (R. R. Rhiger, F. M. Gager, J. R. Marshall). Considers the coaxial *thermocouple-lossy line method of r-f power measurement* for determining transmitter output for various standing-wave ratio load conditions. The construction and calibration of several types of thermocouples are also considered.

411-280A (H. L. Crispell). Describes *measurement of r-f power by the equivalent signal method.*

411-TM-63 (RP-266, U-400) (C. D. Jeffries). Noise tube tester (Type 931 and 931A). This in-

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strument measures the noise level of the tube and indicates its suitability for use. It consists of a light-tight holder with exciting light for tube under test, two-stage video amplifier, 0.5- to 7.5-mc bandwidth diode detector, power rectifier, two 6E5 indicators, calibrated potentiometer, and built-in power supply. After the exciter light intensity has been adjusted to close the eye of one 6E5, the noise output is measured by the percentage of potentiometer resistance necessary to close the eye of the other 6E5.

411-IB-3 (RP-306, H-300). Noise analyzer, 0.2 to 5 mc. By means of a bolometer output power meter this device measures the voltage of the noise generated by a constant-current source in the 0.2- to 2.5-mc and 2.5- to 5-mc bands, separately and together. It consists of an input probe, calibrated attenuator, video amplifier, high- and low-pass filters with cutoffs at 2.5 mc, and the output meter. The accuracy of its measurements is within ± 4 per cent.

411-262 (A-9300, RP-461) (J. R. Duggan). Describes a system for using a commercial *communications receiver (SX-25) as a noise analyzer.* The noise is fed to the antenna terminals of the receiver (which is adjusted to maximum sensitivity) through a cathode follower and attenuator which is calibrated for the frequency range involved in the noise spectra. The attenuator may then be set to produce the same S meter deflection for each frequency, all settings and corresponding frequencies being recorded. Proper corrections for sensitivity variations are made by aid of a signal generator. An auxiliary voltmeter may be substituted for the S meter if it is not feasible to operate at full sensitivity.

411-TM-45 (J. F. Byrne). RCM test equipment summary as of January 1, 1944.

411-279 (H. W. Belles, H. L. Crispell, F. M. Gager). Describes *measurement of microwave receiver sensitivity* by using a test oscillator, lossy cable, and a thermistor bridge. The result is given in terms of the lowest value of the maximum power available from the equivalent signal source required to produce a predetermined receiver output. This is obtained from the attenuation equivalents of two lengths of lossy cable and a power measurement.

923-2 (RP-270) (A. P. G. Peterson). Discusses the behavior of a *crystal rectifier voltmeter* at ultra-high frequencies (300-2,500 mc). The crystal is mounted in a probe fed by a coaxial cable from a source of h-f voltage. The probe is connected to a transmission line measuring system which feeds a bolometer. The report indicates satisfactory measurements if proper technique is used in manufacture and if suitable measurements of h-f characteristics are made.

(January 7, 1944)

5.5 TRAINING EQUIPMENT

Practice Jamming Set, 450-720 mc.

Div. 15	RP-180	Army	AN/UPT-1
RRL	F-2800	Navy	AN/UPT-1

This is a ground-based jammer providing five types of amplitude modulation used to train radar personnel in antijamming techniques. It is a modified form of AN/APT-2 permitting separate or combined modulation with noise (40 kc to 3.5 mc), sine waves (50 and 200 kc variable up to 80 per cent, and 120 c at 25 per cent), and pulses (1.5 μsec, 10-100 kc prf). Unmodulated carrier power varies from 8 w at 450 mc to 2 w at 720 mc. Sideband energy and bandwidth depend upon type and degree of modulation and clipping. It is operated from 60-c power supply.

411-TR-27. Brief description with block diagram, and laboratory report of performance.

411-TR-27A. Results of laboratory measurements and tests on a manufactured model, including photos and performance curves.

411-TM-104 (E. A. Yunker). Brief description and comparison with other types of practice jammers.

411-TM-104 (RP-180, F-2000) (E. A. Yunker). Practice jamming set, 450-720 mc. This equipment is similar to F-2800 in purpose and construction except that it supplies FM (0-200 c with 3-mc sweep) instead of noise modulation and supplies sinusoidal AM at 50, 400, and 0.8 to 5.2 kc, the latter depending upon the frequency of the power supply. Operating power at 400-2,600 c is used instead of 60 c. Brief description and comparison with other types of practice jammers.

Practice Jamming Set, 175-550 mc.

Div. 15	RP-323	Army	AN/UPT-T4
RRL	F-3800	Navy	AN/UPT-T4

This ground-based transmitter is a modified form of AN/APQ-2 supplying the same types of modulation as does F-2800.

411-IB-61. Illustrated description and instructions for installation, adjustment, operation, and maintenance, with schematic diagrams, chart of

counter-settings, and chart of energy distribution.
Oscillator for Practice Jammers, 100 kc or 400 kc.

Div. 15	RP-348	Army	RF-9/UPT
RRL	F-4100	Navy	RF-9/UPT

This Colpitts oscillator provides sine-wave modulation for training purposes with AN/APT-2, /APT-3, or /APQ-2 when plugged into the second video amplifier socket. It modulates at 100 kc, 400 kc, and twice the power-supply frequency, and obtains its power from the modulator strip of the transmitter.

411-TR-17. Laboratory test report on operating characteristics.

411-TM-62 (E. Barrett). Brief description with circuit diagram and photo, and directions for plugging in.

411-TM-104. Brief description and comparison with three other practice jammers.

411-IB-22. Preliminary operating instructions.

411-14 (RP-207, B-502) (R. J. Pierce). Jamming signal generator, 100-350 mc. This oscillator for laboratory study of jamming can be amplitude-modulated by internally generated 100-, 200-, or 500-kc sine waves or by externally generated noise or pulses at frequencies up to 2 mc. Description and preliminary instructions, with parts list, photos, and schematic diagrams.

411-22 (RP-207, B-501) (R. J. Pierce). Jamming signal generator, 100-350 mc. This instrument for laboratory study of jamming consists of a variable-frequency oscillator with variable r-f output (0- to 96-db attenuation) modulated by variable pulses, all indicated by calibrated panel dials. The pulse-repetition rate is variable from 500 to 5,000 c, as controlled by a multivibrator circuit whose output is shaped to provide pulse lengths varying from 1 to 10 μsec. (Two pulses may be provided by aid of a time-delay circuit.) The equipment may also be used as an unpulsed signal generator. Description and preliminary instructions with photos and circuit diagram.

Jamming Signal Generator, 2,400-3,700 mc (RP-191, A-1700).

This 6-ft rack assemblage is used for laboratory testing of radar receivers, for AJ studies, and for instructional demonstration of waveforms due to various kinds of modulated and unmodulated signals. It employs a WE707B low-power r-f oscillator with single-dial control of frequency. A wide variety of a-m and f-m signals are provided by built-in sine-wave oscillator, phototube noise generator, and a pulse unit. The output may be observed by a built-in wide-range (4 mc) oscilloscope, be measured by a bolometer-wattmeter, and be used for receiver testing either by means of an r-f attenuator or by pickup from one of three 12-in. paraboloid antennas covering the frequency range in three bands.

411-TM-2 (Ralph Hoglund). Brief description, specifications, and suggestions for use, with block diagram and photo.

411-IB-18. Detailed description of all components, operating principles and procedures, maintenance, circuit diagrams, photos, and excellent oscillograms of various modulation waveforms.

Antijamming Training Set, 90-270 mc.

Div. 15	RP-160	Army	TPQ-T2
RRL	P-525A	Navy	TPQ-T2

This portable generator of signals having various types of modulation is used in training radar personnel in antijamming techniques. It provides frequency modulation (deviation 5 mc or ½ mc at rate of 40 to 100 c), and amplitude modulation with noise (3½-mc bandwidth), sine wave (approximately 80 per cent at 0.1, 0.3, 1, 3, 10, 30, 100, and 500 kc), or pulses (6, 4, or 1 μsec and prf of 30, 100, or 500 kc). About 0.5-w output is available either at a relatively high-voltage level from a fixed coupling loop or at a lower level from an adjustable output attenuator. A demountable loop antenna can be connected to either output.

411-TR-23. Brief description, block diagram, photos, and summarized results of laboratory performance tests.

411-TR-23B. Brief illustrated description and report of laboratory tests and measurements of manufacturer's models. A number of changes are recommended for improving construction.

411-TM-128A (D. R. Schueck). Interference generator attachment for Mark I trainer.

Div. 15	RP-313	Navy	TS-109/SPA
RRL	E-1300		

This attachment provides various jamming waveforms and means for mixing them with the simulated radar signals produced by a Mark I trainer used to simulate a Mark IV radar. These waveforms include 200- to 220-c and 200- to 220-kc sine waves, 1-μsec pulses at 200-220 kc, and random noise. Their modulation at a lobing rate of 30 c enables an operator to DF on the simulated interference. The device consists of an exciter unit with 6AC7 tubes as sine-wave generators and an 884 as a noise source, a video amplifier, a lobe controller, a lobe inverter mixer, and a power supply. Explanation of operation of circuit and its components includes

SECRET

specifications, block and circuit diagrams, photos, and sketches of waveforms.

411-TM-124 (E-2000, RP-214). Describes adaption of Navy SC radar for use in AJ training.
Jamming Signal Generator, 450-1,000 mc (RP-364, U-700).

This equipment produces various types of jamming signals for training use against the Mark IV and Mark XII radar. The signals may be unmodulated, sinusoidally modulated (AM at 0.15, 150, and 400 kc), pulsed (overmodulation on 100- and 500-kc sine waves at most carrier frequencies), or noise amplitude-modulated with 2-mc r-f bandwidth. Provision is also made for superimposing 25% 120-c modulation on any other type of modulation in order to simulate a jammer with a poorly filtered power supply. It has an output of at least 0.1 w which is fed through a variable attenuator to a dipole antenna that has a fixed bazooka for conversion from dipole to unbalanced line. The noise source is a 6D4 gas triode. The 450- to 1,000-mc oscillator employs a doorknob triode in a butterfly circuit. Carrier level is indicated by a 6E5.

411-TR-42. Brief illustrated description of RRL model of U-700 and report of laboratory tests which indicated satisfactory operation.

411-TR-42A. Report of laboratory tests of manufacturer's model indicated satisfactory performance except as regards proper calibration and ability to withstand vibration and shock tests.

411-IB-77. Description and instructions for operating, adjusting, and maintaining U-700.

411-282 (W-1800, RP-471) (O. W. Whitby). Explains the components and operation of a *DF antenna trainer,* the AN/APA-42T1, for ground instruction in using an airborne rotary antenna, particularly AN/APA-42, to take bearings on a ground-based radar.

966-43 (R. L. Robbins). Describes a *phonograph record of jamming signals* (stepped tone, sweep-through, spark, random noise, etc.) to be used in AJ training of inexperienced personnel.
(December 7, 1944)

RCM EQUIPMENT

ELECTRON TUBES

747-1 (RP-353). A preliminary report on the *resnatron development,* most of which is duplicated in 747-2.
(March 1, 1943)

747-2 (RP-351a) (W. B. Fretter, F. W. Boggs). Traces the evolution in the design and construction of experimental *resnatron high-power oscillator-amplifiers* in the 20- to 100-cm range. An early model was used in Tuba ground-based jammer and a later model was installed in other truck-mounted jamming stations. The report includes a brief review of difficulties due to transit time effects at high frequencies, an account of methods used in calculating the fields in the tube, and a discussion of possible applications to television, dielectric heating, and high-voltage X rays.
(September 21, 1944)

747-3 (RP-351a) (F. W. Boggs). Recapitulates the chronological *development of 10-kw magnetrons* for oscillation in the 43- to 100-cm range. Special attention is given to the choice of a cathode material, to reduction of a fluorescent glow in the output seal, and to methods of cooling the magnet. Data and directions are given for constructing a tube to oscillate in the 59- to 100-cm range.
(July 5, 1945)

867-3 (M. Freundlich). Describes an *ultra high-frequency diode* (158J) suitable for work up to 1,000 mc and forming the inner part of a standard 70-ohm coaxial line. The report includes tests which indicate no effects due to transit time nor resonance. This lighthouse tube is used in the u-h-f power meter described in 867-8 (Section 5.4).
(December 21, 1943)

931-6 (RP-244) (J. P. Blewett). Discusses the *design and performance of the ZP-579,* a 150-w two-anode magnetron that is tunable over the 350- to 750-mc range. The development involves the solution of the problems of adequate cooling techniques, external tuning, minimization of cathode back heating effects, and modulation techniques for barrage jamming.
(February 14, 1944)

931-7 (RP-116) (R. B. Nelson, R. V. Langmuir, J. P. Blewett). Describes the *construction of the ZP-595,* a 10-kw two-anode magnetron for operation in the 400- to 700-mc range and tunable over about 15 per cent of the range. The anode and secondary-emission cathode are water-cooled. A combination of amplitude and frequency modulation fits the tube for use in a barrage jammer.
(February 9, 1944)

931-33 (RP-116) (R. V. Langmuir, R. B. Nelson). Traces *evolution of ZP-595* through concluding research stage. Secondary-emission cathode is found to eliminate back heating trouble and to save cathode power. No conclusive data obtained on life.
(November 19, 1945)

931-12 (RP-396) (N. T. Lavoo). Considers the effect of improved output cavity design on the *amplification characteristics of the L-14* tunable broad-band amplifier, a modified version of the ZP-572 "oil can" tube. It is concluded that a small signal amplifier having good gain and bandwidth characteristics up to 3,000 mc can easily be designed around an L-14 operating on the quarter-wave mode. A power gain of ten times is obtainable with a 10-mc bandwidth, with wider bands obtained at reduced gain. The deteriorating effect of large signals is yet to be investigated.

(August 25, 1944)

931-13 (RP-116) (R. B. Nelson). Discusses the use of a *gold-copper alloy solder* having a melting point at 950-990 C intermediate between the 778-C point for silver-copper alloy and the 1082-C point for copper. This 3/8 Au-5/8 Cu alloy is satisfactorily used for soldering copper to steel, fernico, copper, and gold by techniques described in report.

(May 30, 1944)

931-14 (RP-393). Describes a commercially available form of housing and ring-type Alnico *magnet for 6D4* noise source. The report includes a nontechnical exposition of the desirable characteristics of the 6D4 gas thyratron as compared to the 931 photomultiplier when used for jamming. The 6D4 properly oriented in an optimum magnetic field gives a 5-mc spectrum about 25 db higher than that obtainable from a 931A, much of whose energy is in the 100-mc region.

(December 20, 1944)

931-21 (RP-244) (P. H. Peters). Describes a *magnetron filament regulator* which corrects for back heating by maintaining constant filament resistance. The regulator consists of a motor-driven Variac control element, a correction signal amplifier, and a sampling circuit. It can be used with any load whose impedance is a function of current or voltage to maintain that impedance within ± 2.5 per cent against external factors which would cause impedance changes in the absence of control. The circuit may be modified to act as a voltage stabilizer.

(November 16, 1945)

931-22 (RP-244) (T. R. Holer. Finds that a *decay in the efficiency of 5J29 magnetron* from 30 per cent to 20 per cent after 15 hr or more of running cannot yet be prevented. Although the cause is not definitely established, indications strongly point to secondary emission. As efficiencies drop, evidence of bombardment strain appears in the glass envelope.

(October 22, 1945)

931-29 (RP-244, 430a) (J. P. Blewett, G. Kron, F. J. Maginnis, H. A. Peterson, W. C. Hahn, J. R. Whinnery, H. W. Jamieson). Explains *differential analyzer techniques in tracing electron paths* in vacuum tubes. (The analyzer is an electromechanical device which integrates the fundamental equations for electric and magnetic fields and draws a picture of an electron path under assumed conditions.) The methods are applied to a split-anode magnetron and to a study of transit time effects in lighthouse triodes. The results are useful in predicting behaviors and improving performance.

(November 23, 1945)

931-23 (RP-244, 158f) (D. A. Wilbur, R. V. Langmuir, R. D. Gordon). Tells of the development of 90- to 1,500-mc magnetrons rated at 150-w and at 1,000-w continuous output. The 150-w series consists of ZP-579, -590, -666, -584, -646, -676, -675, and -677. The 1,000-w series consists of ZP-599, -647, and -685 and A-131. The report gives detailed data on the design and operation of each of these tubes, following a discussion of principles applicable to all of them. The lower-frequency tubes are of the split-anode type, while those for the higher frequencies are of the multivane behavior. The report includes numerous photos, sketches, and performance curves.

(November 23, 1945)

931-30 (RP-116) (R. B. Nelson). Discusses the factors which determine the design, construction, and performance of the externally tuned high-power *ZP-636 magnetron* for 100- to 350-mc range. This tube is of the split-anode type with double-ended coaxial structure. It is tuned by sliding shorts symmetrically placed in coaxial lines connected at opposite ends of the tube. The cathode is a heavy tungsten spiral. Output varies from 3,000 w at the center of the frequency range down to 1,000 w at the ends of the range. Efficiency is about 50 per cent.

(November 21, 1945)

931-24 (RP-430a) (R. D. Gordon). Records the development of air-cooled *ZP-633 magnetron* to provide a 25-w output for airborne jammers in the 300- to 1,500-mc range. The tube has split anodes connected across parallel lines which are shorted by sliding contacts. Low efficiency at the higher frequencies suggests that the frequency range be covered by two magnetrons of differing anode-cathode dimensions.

(November 21, 1944)

931-28 (RP-394) (A. M. Gurewitsch, J. S. Hickey, E. L. Strempel, W. H. Teare, J. R. Whinnery). Tells of the uncompleted development of a *5-kw triode for 70- to 350-mc range*. The latest

SECRET

version, L-200, had an indirectly heated barium oxide cathode, molybdenum grid, and water-cooled anode.

(December 8, 1945)

931-32 (RP-116, -156, -157, -158f, -188, -243, -244, -258, -347, -392, -394, -430a, -433, -434) (J. P. Blewett). Summaries work done in developing magnetrons, *noise sources, confusion techniques, and spectrum analyzers.* In addition to results also reported in accounts of individual projects, the most noteworthy conclusion is that the echo from the ionized gases produced during explosions is useless for confusion of enemy radars. The report includes many photos, sketches, and performance curves.

(November 20, 1945)

931-35 (RP-430a) (R. B. Nelson). Tells of preliminary development of *ZP-652 magnetron* for use in a low-power airborne jammer in the 10-cm region.

(November 23, 1945)

1019-1 (RP-158a) (L. Tonks). Discusses the *design of electromagnets for 1-kw magnetrons.* Formulas are derived for the required number of ampere-turns in coils and dimensions are given for iron cores to be used with ZP-597, -612, -615, -616, -638, and -639. For constant power output throughout the frequency range it is also found that magnetron voltage should be inversely proportional and current directly proportional to the square root of the wavelength.

(June 6, 1945)

1019-2 (RP-158a) (H. C. Hertha, R. B. Nelson, T. C. Swartz). Traces the various design and constructional steps in the *development of ZP-616* magnetron to give an output of 1 kw in the 760- to 1,160-mc range. The tube is water-cooled and uses a double-spiral tungsten filament, a J-shaped anode soldered with a gold-copper alloy, fernico bellows, and a fernico-to-glass air-cooled seal.

(September 27, 1945)

1019-3 (RP-158A) (H. C. Hertha). Discusses the use of *vacuum thermocouples in a detector of standing waves* for frequencies around 1,000 mc. They provide a sensitive instrument which does not easily burn out and which eliminates the use of batteries and cures the drifting of readings in a bolometer bridge circuit.

(October 1, 1945)

1019-4 (RP-158a) (A. H. Sharbaugh). Describes a method for the "cold" testing of magnetrons and its application to the study of *parasitic resonance in ZP-597* magnetron. The study results in eliminating harmful resonances which had prevented continuous output of 1 kw in the 21.5- to 30.0-cm range.

(September 18, 1945)

1019-5 (RP-158a) (L. Tonks and associates). Summarizes the development of *Piccolo 1-kw tunable c-w magnetrons* for RCM application in the 500- to 3,600-mc range. The tubes specifically discussed are ZP-594 (460-640 mc), ZP-615 (600-840 mc), ZP-616 (760-1,160 mc), ZP-597 (1,000-1,400 mc), and ZP-639 (1,710-2,610 mc). Mention is made of the evolution of 6J21 from ZP-612 to cover the 2,500- to 3,600-mc range and of the ½-kw L-104 to cover the 8,100- to 10,000-mc range. The discussion comprehensively includes design of cathodes, anodes, interaction space, tank circuits, tuners, and coaxial and wave-guide outputs. The report includes many photos and test curves.

(October 29, 1945)

1019-6 (RP-158a) (R. A. Dehn, W. H. Teare, S. E. Webber). Discusses the design construction and testing of the tunable *L-104 X-band magnetron* having a minimum c-w output of 500 w. The tube has a doubly tapered wave-guide output and a thin untuned mica window. The vane-type anode is of double-strap construction with 12 oscillators. Tuning is accomplished by a "crown of thorns," each thorn being a sector of an annulus shaped to fit the inductance part of the cavity. Preliminary tests indicate coverage of 8,100- to 10,000-mc range.

(October 25, 1945)

1019-7 (RP-158a) (R. I. Reed). Describes the development of the cathode, anode, and tentative tuning mechanism of the *ZP-594 magnetron* operating in the 500- to 670-mc range. The tube has an eight-vaned anode with double-ring strapping and a double-helix tungsten emitter and is rated for an output of 1,000 w.

(October 29, 1945)

1019-8 (RP-158a) (P. W. Crapuchettes, R. I. Reed, R. J. Stupp). Tells of the successful development of the *ZP-597 magnetron* to operate in the 1,000-1,400-mc range with a rated output of 1,000 w. The final tube has a 12-vane anode tuned by a plane C-Ring and recessed flat L-Ring actuated by a Monel bellows and tuning post arrangement. The cathode is a tungsten bifilar filament supported by a molybdenum sleeve. The output connection is 50-ohm coaxial with terminals tapered to permit uniform loading with frequency.

(October 29, 1945)

1034-1 (RP-247) (E. Labin, M. Arditi, J. Glauber, M. Charchian). Traces unsuccessful attempts to develop a 600-mc sealed-off resnatron on the basis of techniques established for demountable tubes.

SECRET

The chief difficulty is due to energy being absorbed from the r-f field by unaccounted for secondary emission.

(May 31, 1945)

1043-1 (NDRC-366) (L. Malter, R. L. Jepsen, L. R. Bloom). Describes a *mica window for wave-guide output magnetrons.* A mica output window has lower dielectric losses than has a glass window and is less likely to fail at high output powers. Reflections are minimized by proper dimensioning.

(December 5, 1944)

1043-3 (L. Malter, J. L. Moll). Discusses the use of *quartz output transformers with wave-guide output magnetrons.* The use of fused quartz instead of a vacuum as a dielectric permits less stringent mechanical tolerances. Performance is found to be practically the same for the two types of dielectric.

(January 15, 1945)

1943-2 (RP-430c) (R. L. Jepsen. Discusses the use of *tantalum cylinder cathodes for c-w magnetrons* designed to deliver 100 w at 1,200 v. For a short life of about 50 hr tantalum is found to give the required high emission and to dissipate back bombardment power more satisfactorily than do available oxide-coated cathodes. Tungsten is not suited for a single-ended cathode with low heater current. The report gives details of design which may serve as a guide in solving similar problems.

(January 15, 1945)

1043-4 (L. Malter). Gives constructional data for a *K-band wave-guide output magnetron.* This is an unstrapped tube wherein the use of alternating cavities of unequal size gives a large frequency separation between the pi and adjacent modes, thus favoring pi-mode operation. Data are also given on the development of quartz output transformers, mica output windows, and other improvements.

(March 1, 1945)

1043-5 (RP-430c) (H. C. Hu). Derives a *scaling formula for designing new magnetrons* by changing the number of slots in an existing tube with known characteristics.

(May 15, 1945)

1043-6 (RP-244b) (L. Malter, R. L. Jepsen, L. R. Bloom, H. C. Hu, J. L. Moll). A sequential account of the uncompleted development of *A-131 tunable X-band c-w magnetron* for use in airborne jammers covering the 8,500- to 10,300-mc range. The latest specifications called for an output of 200 w at 2,000 v. The report is largely concerned with a discussion of problems yet to be solved and recommendations for paths to be followed in seeking solutions.

(November 15, 1945)

1222-1 (RP-332) (A. L. Samuel, J. W. Clark). Recounts the *development of 2K48 and 2K49* local oscillators for 3,000- to 6,000-mc and 5,000- to 10,000-mc search receiver operation, respectively. The important requirements for these low-power vacuum tubes were that there should be no blank regions in the frequency coverage and that they should be easily tunable. Each is a velocity-variation tube of the focused beam reflex type designed for use with an external coaxial cavity whose inner conductor forms an integral part of the tube. Tuning is done with an adjustable piston which varies the effective length of the coaxial cavity. The tube contains an electron gun which directs an electron beam through an h-f gap, defined by holes in two copper disks, and a repeller electrode which, after a critically valued time of transit in the reflection region, redirects the "bunched" beam through the gap where it delivers energy to the r-f field. The report includes laboratory drawings and test specifications for the finished tubes.

(February 28, 1945)

1222-2 (RP-439) (A. L. Samuel). Reports on consulting service on and deliveries of 2K48 and 2K49 tubes.

(September 28, 1945)

1357-1 (RP-158b) (W. G. Wagner). Recounts the evolution of the sealed-off *6J21 tunable magnetron* from the ZP-612 demountable, continuously exhausted prototype. Complete information is given on the design, development, and pilot production of magnetrons delivering 800- to 1,000-w average power in the 2,500- to 3,600-mc range. The tube can be fully amplitude-modulated, with simultaneous FM of the amount required for RCM purposes, and can be tuned to any point in its spectrum within a backlash limit of 4 mc. Features differing from the prototype include a broad-band wave-guide output transformer and glass window, a thoriated cathode, and externally actuated tuning mechanism.

(September 30, 1945)

1430-1 (RP-158c) (A. K. Wing, A. S. Vanderhoof, P. I. Corbell, H. R. Jacobus). Tells of the incomplete development of preproduction models of *1-kw c-w tunable magnetrons* to cover the 600- to 840-mc and the 760- to 1,160-mc ranges (ZP-615 and ZP-616).

(September 29, 1945)

6.2 ULTRAHIGH FREQUENCY OSCILLATORS

411-11 (A-1501, RP-173) (G. E. Hulstede). Describes a *double coaxial cavity type of oscillator*

SECRET

using a GL-446 "lighthouse" tube and tunable with a single dial from 1,000 to 3,300 mc. One cavity terminates the tube's anode-to-grid impedance and the other terminates the grid-to-cathode impedance. Both cavities are tuned by means of sliding plungers connected through metal rods to an external mechanism wherein a mechanical linkage with an adjustable cam provides proper trackage for the plungers. For applications see A-2600, D-1500 (Section 1.2).

411-38 (J-800, RP-168) (J. G. Stephenson). Summarizes results of *tests with early experimental models of GE-L-3* triode as a c-w oscillator in coaxial line tuned circuits. Most of the models were efficient oscillators up to 1,000 mc, with usable power up to 1,200 mc, and were tunable from 300 to 1,100 mc. Optimum output and efficiency required external feedback in the grid-separation circuit (three types described). Maximum power output was limited by mechanical distortion of the grid, amounting to about 30 w at 600 mc.

411-49 (A-3000, RP-205) (J. G. Stephenson, R. L. Henkel). Summarizes results of experiments with *GE ZP-449 triode* as a c-w oscillator in coaxial line tuned circuits described in 411-38. Most of the tubes tested with external feedback oscillated as high as 2,000 mc, delivering 25 w at 500 mc and 6 w at 1,500 mc, using a liquid-cooled anode. Tuning range extends from 465 to 575 mc. Report includes measured characteristics, operating notes, description and diagram of oscillator assembly, and description of tuning methods, feedback, and output coupling.

411-TM-139 (A-3100, RP-286) (R. H. Hoglund). Finds that satisfactory oscillation over the 3- to 6-cm range with 10-mw output can be maintained by a *magnetically focused velocity-modulation tube* (Bell Labs. Exp. 1280 CT) in a wide-band waveguide type of cavity. The tube consists of an electron gun, two gaps, and a drift tube, with collector and disk connections to an external cavity in whose hollow center the tube is mounted. The cavity is a rectangular wave guide operated with one-half wavelength between two tuning plungers driven through a gear train to give full tuning range with single-dial control. A regulated power supply enables operation at three separate voltage modes in covering the frequency range. The report includes performance curves and circuit diagrams.

411-TM-135 (A-3200, RP-295) (F. A. Record). Reviews the difficulties encountered with *microwave c-w power oscillators* and discusses possible means for avoiding them. Consideration of small conventional tubes, telescopic triodes, cylindrical tetrodes, magnetrons, velocity-modulated tubes (klystrons), and positive-grid tubes (Barkhausen) leads to two possibilities: (1) increasing the upper frequency of the high-power, high-efficiency tetrode and (2) increasing the power and efficiency of the high-frequency velocity-modulated tube. Commercial developments of wide-range-tuned magnetrons are under way for frequencies less than 4,000 mc. Slight progress has been made in developing moderate-power klystrons, at low efficiency. A cylindrical structure is desirable for high power and some type of positive-grid operation is advantageous for high frequency.

411-184 (A-3200, RP-295) (F. H. Crawford). Interprets data developed in studying *tunable squirrel-cage magnetrons* of both the cavity-tuned (SD-849) and internally tuned (donutron) types. The resulting theoretical picture of their operation reveals several strong modes of oscillation. That having the longest wavelength is regarded as a loaded cavity oscillation. Those having shorter wavelengths seem to correspond to various numbers of standing waves around the anode circumference. The wavelengths of these latter reentrant-line modes depend upon the radius of the anode and the number and length of the fingers. Steady c-w outputs of around 60 w at 6 cm have been obtained from the donutron (14 per cent efficiency) with a tuning range of approximately 1.3 to 1.

411-249 (A-3200, RP-298) (M. D. Hare, V. Leonard). Describes the materials, mechanical processes, and assembly methods employed in Radio Research Laboratory [RRL] *construction of the donutron,* tunable squirrel-cage magnetron, Models K and L.

411-252 (A-3200, RP-295) (F. H. Crawford, M. D. Hare). Describes the construction and operating characteristics of *the donutron,* a magnetron consisting essentially of a set of interleaving metal fingers arranged to form a multisection squirrel-cage anode. The tube is tuned by the relative axial displacement of alternate anode segments, through flexure of one wall of the cavity in which the anode structure is supported. The construction is much simpler and cheaper than that of a conventional multicavity c-w magnetron of the same power level. This is of the order of 50 w at 40- to 50-per cent efficiency with a tuning range of 1.5:1 with power flat at 3 db. The entire tuning range can be covered by a single value of voltage and magnetic field. The important modes of operation are a long-wave tunable cavity mode and a short-wave resonant reentrant-line mode. The former can be entirely suppressed and the latter enhanced by a special phase-reversing anode. The usual troubles

SECRET

due to mode jumping are almost entirely eliminated. Modes of 4 cm or less have been indicated in cold tests. The report includes many curves and three Rieke diagrams. The discussion covers a wide range of design parameters. Voltage-current characteristics indicate a static impedance of 700-1,500 ohms.

411-70 (A-3700, RP-321) (G. Hok). Summarizes results of preliminary tests on operating characteristics of the Westinghouse (Sloan) *10-kw tunable magnetron*. The report includes a description of the equipment and the test procedure, an outline of the theory of magnetron modulation, and an explanation of how Rieke diagrams are used to determine the load impedance necessary to provide optimum performance. The models tested employed an aluminum-coated cathode with a tungsten filament for supplying the electrons to start emission and oscillation. Because maintenance of emission from aluminum requires occasional exposures to air, the particular tubes used for these tests could not be sealed off and required continuous pumping to maintain vacuum. The electrodes are placed along the axis of a solenoid magnet coil. Frequency is varied by a movable tuning ring which increases the capacitance between the anode segments when moved to the left and reduces the tank circuit inductance when moved to the right. The generated power is transferred into a rectangular wave guide by means of a coupling loop. The anode, cathode, and tuning ring are water-cooled, while the magnet and output seal are cooled by compressed air. The modulator provides a noise output up to 1,000 v peak to peak, with a 5-mc bandwidth for a 300- to 1,000-ohm lead. A typical tuning range is from 310 to 490 mc. Cathode emission was found to be generally satisfactory, but all tested tubes show instability over part of the performance range.

411-70A. A report on *later work on the project just described.*

411-160 (A-3700, RP-321) (G. Hok). Explains seven methods for calculating the approximate *parameters of u-h-f resonant systems* from the results of standing-wave measurements. The methods are applicable to four-terminal networks, such as vacuum-tube tank circuits or systems with distributed constants, where direct measurements are difficult or impossible. They depend upon finding an approximately equivalent circuit in terms of lumped constants, from which are derived the relations between the parameters and the "cold" impedance seen from the output terminals. The values of these parameters are then determined from a plot of standing-wave measurements by aid of graphs and simple formulas. The report reviews the important parameters, discusses equivalent circuits from the viewpoints of accuracy and simplicity of analysis, investigates experimental procedure and sources of error, and presents the analytical foundations for the various methods of calculation.

411-TM-138 (A-3900, RP-295) (F. H. Crawford). Gives preliminary results of measurements of the *noise modulation of ZP 597* at low power levels and relatively narrow modulation bandwidth. The noise source was a 931 photoelectric tube. The results suggest that this magnetron might be usable as a source of power for a jamming transmitter at a power level of the order of 150 w for frequencies from 1,170 to 1,500 mc.

411-TM-138A (A-3900, RP-295) (F. H. Crawford). Gives results of measurements of the *response to noise modulation of a ZP-597* magnetron at 500-w output near 24 cm and of a *ZP-594* at 500- to 1,300-w output near 44 cm. Using unsymmetrically clipped noise from a 6D4 source with high-pass filter cutting off at 1.5 mc, the 597 gave a bandwidth of 44 mc, and the 594 a bandwidth of 6-12 mc at half-power points. The report includes a description, block diagram, and a noise spectrum of the modulator, and tabulated results in terms of both the Rieke diagram and the current-voltage plot.

411-185 (A-3900, RP-417) (F. H. Crawford, M. Pease). Discusses the use of a magnetic diode in the output coaxial line from a magnetron as a method of *magnetron modulation*. The diode acts as a variable-impedance tube whose operation depends upon the presence of a region of very low dielectric constant produced by an electron cloud rotating around the cathode. Any change in anode voltage changes the standing-wave condition in the line by changing the diameter of the electron sheath around the cathode. As this changes the operating point in the Riecke diagram, it changes (modulates) the frequency and amplitude of the magnetron oscillations. The method provides a high-impedance load into which the modulator acts and eliminates d-c plate dissipation. The report includes theoretical expressions and graphs for results to be expected at low r-f fields.

411-130 (A-4100, RP-417) (F. H. Crawford). Preliminary studies of the *response to noise modulation of a ZP-612* tube with gas-tube noise source indicate satisfactory modulated powers and 15- to 20-mc bandwidths, at half-power points, for modulator voltages of 800-1,100 v peak to peak. Observations were made at 2,660, 2,764, and 2,910 mc in the 10.2- to 12.1-cm tuning range. A high-pass filter in the modulator improved the r-f spectra, which

SECRET

were somewhat unsymmetrical, with rather pronounced wings. A marked decrease in cathode emission was noted during continued use; it could always be compensated for by increasing the filament temperature.

411-235 (A-4100/9300, RP-461, 417) (J. C. Turnbull, J. R. Duggan, C. F. Otis, H. W. Welch). Describes *modulation tests of 6J21 magnetrons* with sine-wave, noise, and pulse voltages. The results of these tests were applied toward the development of a magnetron for use as a spot jammer with minimum output of 800 w in the 2,460- to 3,610-mc range.

411-172 (A-9000, RP-461A) (J. F. Byrne). Derives equations for the *efficiency and output power of a Class B power amplifier of noise energy* in terms of the peak, rms, and average values of excitation voltage. The performance of push-pull 813 tubes with 10 per cent clipped noise is computed as a typical example.

411-159 (D-100, RP-416) (R. A. Soderman). Discusses *applications of butterfly circuits* for oscillators in the 100- to 1,200-mc range of frequencies. These are used with type 955 or type 703A tubes in the tuning units for APR-1 and APR-4 receivers and C-1203 spectrum analyzer, as well as in the U-700 and U-1300 signal generators. They are also used in the U/B3000 and GR-720 heterodyne frequency meters as well as in other applications requiring a moderately high Q, broad-band, selective circuit. They are small in size, light in weight, and rugged in construction, but may require close tolerances. The discussion covers both symmetrical and unsymmetrical butterflies and explains reasons and cures for some of the difficulties that arise. The report is well illustrated with sketches, photos, and circuit diagrams.

411-TM-101 (Q-100, RP-186) (R. R. Buss). Concludes that a random-pulsed triode cavity oscillator (*ZP-522*) is a relatively inefficient and ineffective jamming source, unless for possible operation in a frequency region where no other equipment is operable. Constant-rate pulsed operation is almost completely ineffective. No appreciable increase in average power output or in upper frequency limit has been obtainable from pulsed operation, and the size and weight of modulator required for the necessary short, high-recurrence-rate pulses are out of all proportion to the amount of power required for the oscillator.

411-83 (Q-200, RP-204) (J. G. Stephenson, R. L. Henkel). Presents the results of studies of the characteristics and performance of preproduction models of the *ZP-522* triode used as a c-w oscillator and amplifier in coaxial line circuits. With 125-w d-c input the average air-cooled oscillator had an output varying from 46 w at 500 mc to 8.5 w at 1,500 mc, the upper limit of useful operation. Greater power output can be obtained by liquid cooling of the anode. The report describes a single-tube air-cooled oscillator tunable from 350 to 1,500 mc and plate-modulated with wide-band noise (modified for use in Carpet IV). It also describes a push-pull liquid-cooled oscillator delivering 100-w output from 500 to 600 mc. Operated as a Class B amplifier (cutoff bias) the average tube shows a 7-8 db gain of up to 800 mc, with plate efficiency of 40 to 50 per cent. Gain up to 11 db at 600 mc is possible with Class AB operation, but at reduced plate efficiency. The bandwidth at 600 mc was about 13 mc, between half-power points.

411-TM-66 (Q-300, RP-204) (R. L. Henkel). Reports the results of an investigation of the operation of two *A2212* (Nehrgaard) tubes in a coaxial cavity oscillator. The tube readily delivers 100 w of r-f energy at any point between 175 mc (50 per cent efficiency) and 400 mc (30 per cent efficiency). The practical limit for the first mode ($\lambda/4$) operation is somewhat less than 500 mc. Wide-band plate modulation is feasible.

411-TM-65 (Q-600, RP-305) (R. R. Webster, J. G. Stephenson). Concludes, as a result of extensive tests with coaxial line oscillators using lighthouse triodes (*ZP-522 and ZP-449*), that wide-band modulation is limited by the high effective Q of the loaded output cavity (Q varies from 100 to 1,000, depending upon the dynamic impedance of the oscillator tube, the characteristic impedance and number of quarter wavelengths in the coaxial tank circuit, and the degree of coupling of the tank circuit to the load, etc.). The bandwidth obtainable with plate amplitude modulation can be improved from 75 to 100 per cent by simultaneous grid modulation in phase with the plate modulation, but at the expense of linearity. The same improvement is given by a combination of plate and out-of-phase cathode modulation. The report presents evidence in support of these conclusions. Circuit diagrams are given for a push-pull ZP-449 oscillator and for a single oscillator, both for 500-600 mc, and for a single 350- to 1,500-mc ZP-522 oscillator arranged for grid, plate, or combination grid-plate modulation. There are also a number of comparative spectrum curves and other pertinent diagrams.

411-126 (Q-800, RP-378) (W. R. Rambo, L. D. Tuck, S. W. Howe). Details performance methods and results for 1-kw *X-124 and X-139 beam tetrodes* (resnatrons) proposed for use as 500- to

600-mc ship-borne jammers. These tubes have a thoriated tungsten filament in the form of an 18-wire cylindrical cage, two tantalum grids (control and screen) in the form of an 18-wire open-ended cylinder, and a copper anode in the form of a slotted cylinder, water-cooled in the X-124 and air-cooled in the X-139. Electrons pass from each filament wire as a radial sheet focused between grid wires into the anode slots. The screen grid is operated at a high positive potential to reduce transit time and also to shield the cathode from the anode, enabling anode current to be shifted into proper phase relation with anode voltage by adjusting the phase of the driving voltage. Coaxial cavities, tuned by plungers, extend in both directions from the plane of the grid. In its present developmental stage the tube is found to be unsatisfactory for the contemplated application. Best performance was given by an X-124E operating as an amplifier with only 30 per cent anode efficiency for 1.2-kw output at 500 mc. In the report various redesign features are suggested.

411-116 (Q-1000, RP-169) (W. R. Rambo, L. D. Tuck). Describes experiments with *GL-522 as a third-harmonic generator*. The best result was 3-per cent anode efficiency for an output of 2 w at 1,700 mc. Tuning is critical.

411-241 (Q-2000, RP-286) (J. J. Wedel). Presents *tuning curves for 2K28 (McNally) tubes* in radial cavities to oscillate in the 4- to 33-cm range of wavelengths. The curves are obtained by theoretical extensions from experimental data and are useful in calculating radial cavity dimensions. Tube impedance curves are also given for use in designing nonradial types of oscillators. Lumper-capacity representation of the 2K28 is shown to be valid down to wavelengths of at least 7 cm.

411-175 (G-2600, RP-295) (F. Bloch). Analyzes the *stationary states in a cylindrical magnetron* when a steady voltage is turned on to maintain a small current. The solution is based upon consideration of electronic motion under the influence of a static magnetic field parallel to the axis of the cylindrical magnetron and of a radial electric field which is defined as a function of time and of an electron's distance from the axis. Emission is limited by space charge and the emitted electrons are initially assumed to rotate in circular orbits around the cathode. The analysis indicates that the circular orbit assumption breaks down when sufficient time elapses after the current ceases. This further indicates the possibility of transitory states during which electrons are constantly emitted from and returning to the cathode. No safe conclusion can be reached without adequate methods for their investigation.

411-284 (A-9000, RP-461) (H. C. Early, H. W. Welch). Discusses the design and use of electromagnets in circuits to provide *self-regulating field excitation for c-w magnetrons*. Because of consequent wide range of tuning with no adjustment of anode voltage, prevention of oscillation in a parasitic mode, and easy regulation of power output, the method is useful in developmental and experimental work as well as in equipment used in the field.

6.3 EFFECTIVENESS OF VARIOUS TYPES OF MODULATION

411-TM-23 (A-3600, RP-197) (W. R. Rambo). Summarizes results of studies of the *effectiveness of mechanical* FM, electronic FM, and combinations of the two in high-power ground jamming of communication receivers in the 40-mc band. Modulation was by random noise and by a 120-c sweep signal supplied from a motor-driven rotating variable condenser. The scheme produced satisfactory jamming signals in the Fuge 16 receiver but was ineffective against a-m receivers equipped with noise limiters.

411-2 (B-500, RP-207) (J. F. Byrne, R. J. Pierce). *Tests* with laboratory equipment *simulating a typical radar system* using Type A presentation show that a jamming-to-signal power ratio of 34.0 db is required for c-w jamming, of 17.5 db for modulated 100-kc sine-wave jamming, and 7.9 db for noise-modulated jamming (0-200 kc). The ratios become 60 db, 26 db, and 7.9 db, respectively, if the receiver be equipped with antijamming circuits (described in detail). The conclusion is that noise modulation giving a signal at least 10 db higher than the reflected signal and containing frequencies above 200 kc is most effective in jamming. A receiver can be partially protected against jamming by means of an automatic biasing circuit and a 200-kc high-pass filter with switch to permit use only under jamming conditions.

411-31 (B-500, RP-207) (R. J. Pierce). Describes and instructs in the use of an *artificial radar system and jammer* for measuring or demonstrating the effects of jamming under controllable conditions. The radar system produces simulated echoes which are variable in carrier frequency (100-350 mc), amplitude (max r-f output varies between 3.0 and 0.2 v with 96 db continuously variable attenua-

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tion), length (1, 2, 5, 10, and 20 μsec), range (2, 5, 10, 15, 35, 70, and 150 miles), and azimuth (to simulate a moving target). It provides Type A and B presentation and has means for producing a main pulse and one echo, or two pulses of differing ranges. (See 411-22.) The jammer's tuning range and output are the same as the radar's. It may be modulated by sine wave (5-2,000 kc), noise (5-2,000 kc), or pulse (20-200 kc, 1-20 μsec). (See 411-14.) The report includes photos and circuit diagrams.

411-55 (K-400, RP-186) (D. W. Taylor, D. A. Peterson). Summarizes observations of experimental *jamming of Type A presentations* with sine-wave AM, noise AM, and direct noise. The results indicate that sine-wave AM is not effective, noise AM is effective (especially with close clipping), and direct noise is effective (especially at high prf's). Estimates of effectiveness are based upon the ratio of jamming power to signal power (J/S), assuming that the receiver is not overloaded and that the pips can be detected half the time. The report includes a description of the synthetic radar system and Dina jamming generator used in the investigations.

411-65 (K-400, RP-186) (D. W. Taylor, D. A. Peterson). Summarizes observations of experimental *jamming of Type A presentations* with sine-wave FM, noise FM, and various combinations of AM and FM. Estimates are based on same assumptions as used in 411-55. The results indicate that sine-wave FM is not effective and noise FM is effective (especially with clipped noise, large frequency deviation, and optimum bandwidth). Addition of noise AM to sine-wave FM yields about the same effectiveness as did the best case of noise FM; further addition of sinusoidal FM having proper frequency deviation enhances the effectiveness. The results from sine-wave FM plus noise FM were inferior. The report includes performance curves and sketches, with detailed comment on each case. It also includes a description of the f-m, a-m generator used in the investigations.

411-71 (K-400, RP-186) (D. W. Taylor). Summarizes observations of experimental *jamming of Type A presentations* with AM, FM, and Dina *when the receiver is overloaded.* When the i-f amplifier is overloaded, the jamming effectiveness of sine-wave AM and FM is increased but is still very inefficient, that of noise FM is first increased and then decreased, and that of Dina is increased. When the video amplifier is overloaded, the effectiveness of all these types of jamming is increased by an amount which is least in the case of Dina and greatest in the case of sine-wave AM and narrow-band clipped noise AM. The report includes performance curves and detailed comment about each case.

411-75 (K-400, RP-186) (D. W. Taylor, J. M. Moran). Summarizes observations of experimental *jamming of Type A presentations* with constant-amplitude periodic and random pulses. The results indicate that periodic pulses are noneffective and that the effectiveness of random pulses increases with increase in the bandwidth of the noise which triggers the pulses. No significant change is caused by overloading the i-f or video amplifier provided that the bandwidth of the triggering noise is about five times that of the receiver. If it drops to two and one-half times greater, i-f overloading greatly decreases the jamming effectiveness and video overloading slightly increases it. The report includes a description of the random-pulse generator employed in the investigations, showing a block diagram with tube complement and corresponding pulse shaping.

411-80 (K-600, RP-186) (D. W. Taylor, J. M. Moran). Summarizes observations of experimental *jamming of Type B presentations* by means of Dina, sine-wave AM and FM, noise AM and FM, and periodic and random pulses when the i-f and video stages are not overloaded. All of these types of jamming are found to be much more effective against a normally loaded receiver in a B scope than in an A scope. The effectiveness for each case is given by detailed comment and curves with respect to such factors as antenna scanning rate, video gain, J/S ratio, modulation, etc. The report includes a description of a novel device for simulating antenna patterns.

411-85 (K-600, RP-186) (D. W. Taylor). Summarizes observations of experimental *jamming of Type B presentation* when the i-f or video stages are overloaded. An increase in the degree of i-f overloading caused (1) a decrease in the effectiveness of jamming with noise AM and Dina, (2) a slight increase in the effectiveness of noise f-m jamming, (3) an increase in effectiveness of low-frequency sine-wave FM or AM, and (4) an increase in effectiveness of relatively high-frequency sine-wave f-m and a-m jamming. Except for relatively high-frequency sine-wave FM, an increase in video overloading caused an increase in the effectiveness of jamming in all cases. These results are applicable to the particular receiver employed in the tests; their relevance to other radar receivers can be determined only by similar studies with each receiver. The report includes an account of the test methods employed and plotted curves for the various reported results.

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411-248 (G-300 and 500, RP-103 and 217) (D. W. Taylor). Summarizes the results of laboratory studies of the *effectiveness of jamming* radar systems. Periodic jamming (sine-wave AM or FM and periodic pulses) is found to be completely ineffective against deflection-modulated scopes whose i-f or video stages are not overloaded. An intensity-modulated scope is susceptible to both periodic and random jamming. Random jamming, including noise AM or FM, random pulse, and Dina, is effective against deflection-modulated scopes to a varying degree. Effectiveness of noise AM is increased by increasing sideband power either by increasing percentage of modulation or by clipping (provided that the bandwidth of the clipped noise is about ten times that of the receiver). Increase in clipping and in frequency deviation increases the effectiveness of f-m noise (provided that an optimum bandwidth is used). Random-pulse jamming is most effective when the upper frequency limit of the triggering noise is about five times the bandwidth of the receiver.

411-238 (G-2700, RP-299) (D. Park). Discusses an 8th Air Force *appraisal of RCM* based upon consideration of battle damage to aircraft. Analysis of the data with regard to Chaff leads to the estimate that the chances are about 70 to 30 in favor of a Chaff-protected squadron as compared to one on the same mission not so protected. No quantitative conclusions are possible with regard to electronic jamming beyond a general indication that it interferes more with search and early engagement than with the direction of fire at any particular formation.

411-7, 7A (F-1900, RP-305) (W. D. White). Analyzes *energy distribution between carrier and sidebands* for half-wave AM, full-wave AM, and FM carriers when each is modulated by random noise. It indicates that, for the same amount of radiated power in a noise signal, FM gives five times and half-wave AM gives three and one-half times the sideband energy given by full-wave AM. Similar analyses for suppressed carrier (balanced modulator) conclude that, while it is excellent in theory, it will have little practical value until suitable u-h-f modulators can be built.

411-29 (G-100, RP-181) (D. Middleton). Calculates the *spectra resulting from various combinations of AM and FM by noise.* For barrage jamming, AM or FM by noise, superimposed on sinusoidal FM, should be more effective than AM or FM by noise alone. The introduction of sinusoidal FM serves to spread the overall spectrum, thus increasing the barrage width without destroying the uniformity of the jamming spectrum. Four combinations of AM, FM, and sinusoidal FM are considered and found superior to sinusoidal FM alone. The results are based on considerations of relative spectral uniformity, spectral width, and the quality of the modulating noise, i.e., whether it is random or highly clipped.

411-51 (G-103, RP-181) (J. H. Van Vleck). Calculates the *spectra which result from clipping* an unmodulated noise band (Dina) and from a carrier modulated by clipped noise. It indicates practically no distortion in either if they are clipped at about 1.4 times the rms level after clipping. Even in cases of extreme clipping, spectral nonuniformity causes very little waste of power. Clipping is found to reduce peak power requirements and to lessen waste of power in the carrier frequency. Clipped noise is found to be fully as effective as unclipped noise having the same spectral distribution provided the receiver width is small compared to the barrage width.

411-86 (G-104, RP-181) (J. H. Van Vleck, D. Middleton). Presents a theoretical examination of the *relative merits of visual, aural, and meter detection of radar signals* in the presence of noise. The report consists of two parts: (1) a descriptive survey of results and (2) a mathematical discussion of the behavior of a superheterodyne receiver when a pulse-modulated carrier enters the device and is rectified in the presence of noise. Visual detection is considered in terms of the spreadout image presented by an A scope, in which the criterion for signal detectability involves the ratio of peak signal to mean noise background. In aural or meter detection, where one listens to or measures the fundamental or low harmonic of the prf, the important ratio is that of the signal energy in one particular harmonic component to the noise energy in the frequency region surrounding this component. The metering scheme may be either periodic (when the rectified current is passed by a narrow-band audio filter tuned to the prf and then rectified before being applied to the meter) or aperiodic (when the rectified current is fed directly to the meter and the d-c component takes the place of the harmonic component).

The sensitivity of any method depends upon the width and shape of the i-f response, the pulse length, and the prf. In aural or meter reception the duration of the gate (to reduce the noise background by the fraction of time that the gate is open), the width of the audio filter, or the time constant of the meter, are also to be taken into consideration. Knowledge of the prf is not necessary

in the case of the aperiodic meter and the ear, which can discriminate frequency (equivalent to surrounding the signal by a certain effective bandwidth). All of these factors are discussed in detail, with particular emphasis on the optimum i-f filter design to provide maximum signal-to-noise ratios. For both visual and aural detection this design is found to be expressed by a filter frequency characteristic which is the Fourier transform of the pulse. The best pulse for visual detection is the Fourier transform of the filter frequency response, whereas long pulses give the best results in audio or meter detection. The quadratic detector is appreciably better than the linear detector only for intense signals. By means of gating and long time constants (which tactical considerations may make difficult of accomplishment), meter methods can potentially be made more sensitive than the A scope.

411-86A (G-104, RP-181) (D. Middleton). Examines the *low-frequency output of a detector having* an essentially *half-wave quadratic response.* This is considered as a particular case of a general theory of quadratic rectification of a modulated carrier in the presence of noise, which theory is also outlined. The powers of the transmitted l-f noise and signal, and their spectral ordinates, are each shown to be one-quarter of their corresponding values for the full-wave quadratic detector. Consequently there is no change in the signal-to-noise ratios used in 411-86. The conclusions of the theory also remain unchanged, provided that attention be restricted to low frequencies and that the input noise band be narrow compared with the bandwidth of the i-f amplifier of the receiver.

411-TM-41 (G-100, RP-81) (D. Middleton). Outlines a general theory for the *rectification of a modulated carrier in the presence of noise* (such as that from the i-f output stage of a receiver) and derives an equation for the (mean) envelope of the output wave from an unbiased linear rectifier. The general method is an extension of the theory developed in 411-51. The equation is found to be equivalent to other previously derived special cases of this general noise theory. It was intended that this outline be the basis for attacking many specific noise problems.

411-32 (G-200, RP-182) (J. H. Van Vleck). Investigates the *efficiency of a series of pulses for barrage jamming.* To cover barrages of the order 10 mc the pulses must be short, of the order 0.1 μsec or less. The pulses should be irregularly spaced, with a mean interval less than the characteristic time characteristic of the receiver bandwidth, i.e., less than a microsecond if this width is about 1 mc. With such a pulse system the energy wasted in the carrier is small.

411-TM-29 (G-200, RP-182) (J. H. Van Vleck). Mathematically analyzes *jamming effect of slow jittered FM* (wide-swing slow mechanical FM on which is superimposed a smaller swing noise FM) on phone reception of communications. The spectrum at such a jamming signal consists of a discrete portion composed of harmonics of the mechanical FM and a continuous part. Since the energy of the discrete portion affects only certain nerves in the ear, its jamming effectiveness is very small as compared with that of the continuous portion. The best obtainable results of rapid, high-amplitude jittering put half the energy into the continuous portion.

411-56 (G-300, RP-217) (D. Middleton, M. Steinberg). Outlines the requirements, as suggested by theoretical considerations, for a possible *use of various types of frequency modulation* in conjunction with AM or FM by noise to provide sufficiently wide and uniform barrages for the jamming of radar or communication systems. Frequency modulation by sinusoidal, unsymmetrical and symmetrical sawtooth, and square waves is considered. Modulation with an unsymmetrical sawtooth wave, if practically obtainable, is the most effective method for jamming either radar or communications systems. For radar, either sinusoidal or symmetrical sawtooth wave modulation is also effective, while the symmetrical sawtooth wave may be used for communications. It is found that the sideband separation should be not less than one-half the effective video or audio bandwidth of the receiver to be jammed and not greater than one-fifth the half barrage width. The spectrum is sufficiently uniform for barrage jamming of radar systems if half the barrage width is not less than 5 times or more than 25 times the FM sweep frequency. The corresponding figures for jamming communications are 50 and 3,000. The width of the noise band should be about three-fourths the sideband separation.

411-TM-26 (G-301, RP-217) (T. S. Kuhn, L. Hoffman). Studies the *spectra due to simultaneous sine-wave AM and parasitic FM* in a self-excited oscillator. The results are plotted to show spectral distribution (amplitude of first four sidebands relative to the carrier after modulation) as a function of the modulation index (K = frequency deviation/modulating frequency) from $K = 0$ to $K = 1.5$ for phase differences of 0, 15, 45 and 90 degrees between AM and FM. By estimating the value of K and the phase difference it is then possible to judge the lack of symmetry in the spectrum, or vice versa.

6.4 ANTENNAS

NDC-rc-100 (Suppl. No. 1) (G. Sinclair). Discusses methods for *measuring aircraft antenna patterns* by means of models and shows a number of representative three-dimensional patterns for mountings on various parts of aircraft. The shape of a pattern is found to be influenced by reflection, diffraction, and resonance in the structure of the aircraft. Knowledge of these factors makes it possible to estimate radiation patterns for various antennas for many conditions.

(August 31, 1942)

NDC-rc-100 (Suppl. No. 2) (G. Sinclair). Presents sample radiation *patterns for antennas on aircraft and tanks* and briefly discusses the measurement of *antenna impedances* by means of models. It is found that patterns for the horizontal and vertical planes are almost as useful as three-dimensional patterns and are much easier to obtain.

(August 24, 1943)

NDC-rc-100 (Suppl. No. 1) (G. Sinclair). Describes a method for determining *tank antenna patterns* by means of models. The lobes in the patterns for a model in free space are caused by reflections from the principal surfaces of the tank. Diffraction and resonance have little influence. Ground-reflected waves affect only those antenna radiations at 15-20 degrees above the horizon.

(September 24, 1942)

NDC-rc-100 (G. Sinclair, E. C. Jordan). Indicates the *effects of airplane structure on polarization* of airborne antennas by means of patterns obtained from models. Examination of these patterns may aid in predicting the pattern for a proposed airborne antenna.

(November 17, 1943)

104-4 (77, RP-399-404) (G. Sinclair, W. Rife). A final report on *model measurements of antenna patterns and antenna impedance*. Results at pattern measurements are satisfactory and have greatly aided in the design and development of all types of antennas. Preliminary impedance measurements indicated large errors around the antiresonant region of an antenna. Progress has been made in the construction of suitable standard impedances for calibrating models.

(October 30, 1945)

411-100 (A. W. Alford). This comprehensive treatise catalogs 26 RRL production types of *antennas and antenna systems for RCM* in order to facilitate the proper choice, installation, and servicing of a given type for a desired purpose. For each type there is a detailed statement as to purpose, description, specification, impedance characteristics, radiation patterns, mounting location and instructions, maintenance, and list of types having overlapping frequency ranges. These detailed listings are prefaced by a brief discussion and explanation of such terms as antenna pattern, gain polarization, standing-wave ratio, and line-balance conversion units. Emphasis is placed on the need for taking both radiation pattern and standing-wave ratio into account when selecting an antenna for a given application. The chapter on installation includes a chart indicating possible antenna locations on an airplane.

411-TM-22 (G-408, RP-107) (E. Fubini, P. J. Sutro). Discusses the *frequency characteristics of a bazooka*, a particular type of transformer for feeding a balanced load from a single-ended line. Insertion of a pair of properly designed quarter-wave matching sections between the transformer and a load having a higher characteristic impedance is found to keep the standing-wave ratio below 1.25:1 for frequency bands of the order of 4:1. Design parameters are given for matching a 50-ohm unbalanced line to 128-ohm and 150-ohm balanced line.

Thick Stub, 70-400 mc.

Div. 15	RP-138	Army-Navy
RRL	M-313	AT-36APT (150-220 mc)
		AT-37APT (113-150 mc)
		AT-38APT (93-113 mc)
		Slant Mount—AT-41APT (150-220 mc)
		Slant Mount—AT-42APT (113-150 mc)
		Slant Mount—AT-43APT (93-113 mc)

Used with SCR-587, ARC-1, APR-1, 2, and 4 for vertical polarization. Consists of copper-plated, compregwood mast in rectangular mount. Copper area is connected to type N connector by tapered copper "dog-ear" whose shape and mounting are important factors in providing wide-band feature.

411-TM-92 (C. M. Daniell, M. J. White). Brief description, characteristics, photos, and graph of impedance versus frequency.

411-153 (P. L. Harbury). Illustrated description of various types of stubs and mounts, discussion of theory of operation, and instructions for installation, maintenance, and cabling.

411-TM-93 (C. M. Daniell). Photos and charts of electrical characteristics for stub and cone assembly, 100-400 mc, and 300-1,000 mc.

Div. 15	RP-138	Army	AS-25/APR-2
RRL	M-801	Navy	AS-25/APR-2

Obsolete design for use with APR-2, replaced by M-313. Consists of a modified AN-104B stub for the lower-frequency range and a 60-degree cone

with a 90-degree cap for the higher-frequency range.

411-TM-79 (H. C. Singleton). Description, sketches, photos, graph of impedance versus frequency of cone, 300-3,300 mc.

Div. 15	RP-138	Army	AT-49/APR-4
RRL	M-2101	Navy	AS-49/APR

Used with SCR-587, ARC-1 for 290- to 1,650-mc range and with APR-1 and APR-4 for 300 to 3,000-mc range, mounted for either vertical or horizontal polarization. It consists of a 60-degree cone housed in a supporting nacelle. The pattern is nondirectional in a plane perpendicular to the axis of the antenna.

Cone, 1,000-3,000 mc.

Div. 15	RP-138	Army	AS-44/APR-5
RRL	A-2612	Navy	AS-44/APR-5

Used with APR-5 for vertical or horizontal polarization. Pattern is nondirective perpendicular to axis of cone. Polarization depends upon mounting, whether vertical or horizontal. Structure includes 700-mc high-pass filter, to minimize spurious responses from lower frequencies. A-2602 is housed in a pressurized jacket, whereas A-2612 requires a blister.

411-TM-77 (H. C. Singleton). Specifications, photo, and dimensional drawing for A-2602.

411-TM-113 (P. L. Harbury). Modified specifications, description, photo, assembly drawing, standing-wave and impedance characteristics, and suggestions for installation.

411-TM-113 (P. L. Harbury). Modified specifications, description, photo, assembly drawing, standing-wave and impedance characteristics, and suggestions for installation of cone, 1,000-3,000 mc.

Div. 15	RP-138	Army	AS-125/APR
RRL	A-2608	Navy	AS-125/APR

Used with APR-5 for vertical or horizontal polarization. General features same as A-2612 except that cone is tilted 55 degrees to base plate and requires blister. Inclination of the axis minimizes null in direction of axis, thus providing fairly uniform radiation for horizontal polarization when antenna is mounted on side of airplane.

Waveguide, 3,000-6,000 mc.

Div. 15	RP-291	Army	AS-45/APR-6
RRL	A-2701, R-1000	Navy	AS-45/APR-6

Used with APR-6. Installation comprises a wave-guide antenna and plastic hood (R-1004) and one of three optional types of wave-guide connections to the receiver (1 x 2 in., Toll Ticket Tubing, or 1½ x 3 in., whichever is more available or mechanically convenient). Condensation of moisture, with consequent high attenuation of signal, is prevented either by heating the system or by silica gel in a sealed system. The antenna pattern in the plane perpendicular to the broadside of the guide is approximately a cardioid (equal gain over 180 degrees ± 90 degrees from guide axis) and in plane perpendicular to narrow side of guide has equal response over 40 degrees ± 20 degrees from guide axis. Two sections (with a Y joint) may be used to feed a single receiver simultaneously from two antennas pointing to port and starboard.

411-TM-71 (W. G. Wadey). Instructions for installation of transmission lines, flanges, tapered and Y sections, and antennas, illustrated with sketches and photos.

411-TM-88 (R-1012, RP-286) (W. G. Wadey). Description of a convenient type of fastener for quickly coupling two wave-guide sections.

411-TM-80 (H. C. Singleton). Brief discussion of salient features, with photos, assembly sketch, and curves of standing-wave ratio of thick dipole, 75-300 mc.

Div. 15	RP-138	Navy	AS-56/SPR-1
RRL	M-2408		

Used with SPR-1 for either vertical or horizontal polarization, depending upon mounting. Requires M-2406 conversion unit when used with unbalanced load.

Double-cone Assembly, 225-1,000 mc.

Div. 15	RP-138	Navy	AS-57/SPR-1
RRL	M-2409		

Used with SPR-1 for either vertical or horizontal polarization, depending upon mounting. It consists of two 60-degree cones supported by a cylindrical nacelle. Requires M-2410 conversion unit when used with unbalanced load.

411-TM-81 (H. C. Singleton). Brief discussion of salient features, with photos, assembly sketch, and curves of standing-wave ratio.

411-TM-55 (E. L. Bock). Tests of the comparative performance of M-2409 and M-801 with semi-circular ground screen indicate that for some types of installation for vertical polarization M-2409 has a significantly greater response and for horizontal polarization, less directivity than has the M-801. The line length variation is greater in the case of M-2409. Various suggestions are given for using one of each type in order to provide adequate search coverage. The report includes photos, field patterns, and graphs of standing-wave ratios.

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411-IB-44. Illustrated description, preliminary instructions for installation, operation and maintenance, and curve of standing-wave ratio versus frequency of antenna selection switch.

Div. 15	RP-138	Navy	SA-14/APR-1
RRL	M-2404, -2413		SA-44/APR-1

411-IB-41. Antenna selection switch, frequencies up to 3,500 mc.

Div. 15	RP-138	Army	SA-44A/APR
RRL	M-2415	Navy	SA-44A/APR

This six-position switch connects six or fewer pieces of equipment to one antenna or one piece of equipment to six or fewer antennas. When installed in a 50-ohm concentric line the switch introduces a standing-wave ratio of less than 1.5 to 1 for frequencies up to 3,500 mc and of less than 3 to 1 for higher frequencies up to 5,000 mc. Illustrated description and instructions for installation, operation, and maintenance.

TMR-48E. Minor changes in drawings to supersede those in previous TMR's.

411-114 (RP-138, M-6301) (E. L. Bock, J. A. Nelson). Brief illustrated description, graph of standing-wave ratio, and patterns of horizontal and vertical planes of balanced dipole and reflector 275-325 mc. This antenna can be mounted at any point below the top of a mast. It consists of two modified M-1201 antennas fed in phase and mounted back to back on either side of the mast. Its pattern is substantially circular in the horizontal plane.

Skirted Stub, 275-325 mc (RP-138, M-6302).

This antenna is designed to be mounted at the top of a mast. It consists of a 9⅞-in. stub fed against a 9⅞-in. skirt. Its pattern is circular in the horizontal plane.

411-114 (E. L. Bock, J. A. Nelson). Brief illustrated description, graph of standing-wave ratio, and patterns of horizontal and vertical planes.

411-120 (J. A. Nelson). Describes the M-6302 as a vertically polarized antenna designed for vertical mounting on the rudder of a TBF airplane. The report includes performance curves for various mountings.

TMR-252. Constructional data on M-4012 for 250-500 mc.

TMR-253. Constructional data on M-4013 for 500-935 mc.

TMR-254. Constructional data on M-4015 for 90-147 mc.

TMR-255. Constructional data on M-4008 for 88-175 mc.

TMR-256. Constructional data on M-4011 for 134-257 mc.

TMR-262. Report on vibration tests and voltage standing-wave ratio for M-4011.

411-291 (RP-303) (J. Nelson, H. Horton, D. Wilhoit). Describes the various antennas in the M-4000 series (81-203 mc), giving photos and performance curves. The report illustrates laboratory procedure in designing an antenna to meet certain specifications. These streamlined antennas are intended for low-speed patrol aircraft, such as PB4Y-2, at speed up to about 500 mph. They are tilt-mounted at 45 degrees, with one for the same frequency range on each side of the plane. Each is fed by a separate transmitter to provide overlapping patterns with 360-degree coverage. M-4003 has a range from 81 to 111 mc, M-4004 from 111 to 152 mc, and M-4005 from 144 to 203 mc.

411-TM-54 (C. M. Daniell). Brief description, characteristics, photos of two crossed, bent dipoles, 505-580 mc.

Div. 15	RP-303	Army	AS-69/APT
RRL	M-2202	Navy	AS-69/APT

Used with APT-2, APT-5, and APQ-1 for vertical, horizontal, and rotating polarization, and with APQ-9 for rotating polarization. It is so designed that the transmitted energy is directed primarily downward from the plane. The two dipoles are adapted for operation with a single transmitter by means of a quarter-wave phasing and matching section, and for operation with two transmitters by means of a pair of transformer sections which make the impedance of one dipole with a transformer equal to that for the combination used with a single transmitter. The assembly is housed in a Lucite dome outside the skin and in an iron box inside the skin.

411-TM-53 (C. M. Daniell). Purpose, characteristics, photos, parts list, construction drawings, field pattern, and impedance graph of two crossed, bent dipoles, 520-580 mc (RP-138, M-2201). Antenna resembles M-2202 except that it is not fitted with transformer sections for operation with two transmitters.

411-IB-33. Brief illustrated description of M-2803 and M-2804 with directions for installation of two stubs and balun, 150-210 mc (RP-303, M-2804). Used with APT-1 and AM-18/APT for horizontal polarization. Assembly comprises two AT-36/APT, one M-2802 balun, and two equal lengths of RG-9U cable. The balun maintains 180-degree electrical phase relation between the radiating elements.

411-TM-122 (C. Driscoll). Brief description and

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discussion of installation, four field patterns, and a curve of standing-wave ratio versus frequency for bent, balanced-sleeve dipole, 195-295 mc, 280-490 mc, 400-590 mc.

Div. 15	RP-303	Army	AS-181/APT
RRL	M-3203	Navy	AS-181/APT

Consists of a permanently installed cylindrical mount (13 in. long) and three interchangeable antennas producing horizontally polarized radiation, distributed in a pear-shaped horizontal pattern with the principal lobe forward. Each antenna may be plugged into the mount and consists of a balanced-sleeve dipole bent into a Vee having an included angle of 100 degrees.

Fishhook Antenna, 440-660 mc.

Div. 15	RP-303	Army	AS-251/AP
RRL	M-2204	Navy	AS-251/AP

Designed for use with AN/APT-2 in all polarizations, this antenna has a single-lobed, circularly polarized field pattern approximately cosinusoidal in shape in all planes through the axis of the lobe. It consists of a pair of crossed-sleeve dipoles housed in a Lucite nacelle. The dipoles are fed approximately 90 degrees out of phase by means of a phasing unit which is an integral part of the input.

411-216 (J. Allen). Gives results of laboratory tests of *performance of M-2204 when mounted in metallic recesses* of various forms. The most satisfactory field patterns and circularity of polarization were obtained when the antenna system was mounted in a parabolic reflector 6½ in. deep and 36 in. in diameter. A Lucite cover for the recess does not substantially impair the results.

411-298 (A. W. Alford). A summary report on fishhook antennas.

411-IB-65. Preliminary instruction sheet giving electrical and physical characteristics, photos, curves of standing-wave ratio, and potential unbalance.

Horn-Type Antenna, 2,310-4,000 mc (RP-303, M-4902).

This circularly polarized antenna comprises (1) transformer consisting of a wave-guide section fed by the center conductor of a short coaxial cable from the transmitter, (2) polarizer consisting of a 10-cm length of wave guide shaped to resolve the exciting wave into two modes at right angles, (3) a phasing section consisting of a nearly square wave guide whose walls are at a 45-degree angle from those of the transformer and which is fitted to receive a crystal detector and r-f filter unit whose output is fed to the indicating meter, and (4) a 9½-in. diameter horn with a 130-degree flare. The antenna provides a substantially circularly polarized radiation, distributed essentially in a single-lobed, symmetrical pattern about 60 degrees wide between half-power points. When mounted against a ground plane, the radiator has a gain of about 10 db over an isotropic radiator.

411-IB-71. Illustrated description and explanation of theory of operation, preliminary instructions for installation, adjustment, operation, and maintenance, field patterns, graph showing less than 3-db deviation from circularity of polarization throughout greater part of frequency range, and graph of standing-wave ratios.

411-294 (P. Keeler). Gives preliminary design information and characteristics of M-4905, a modification of M-4902 to provide circular polarization, for low-level bombing attacks against radar-protected installations. In a partly successful attempt to accomplish this purpose, the phasing and flared sections of M-4902 were replaced by a sectoral horn to give a beam of the required shape. The report includes an account of the operation of M-4902 and M-4905 and a discussion of the parameters for determining the M-4905 characteristics, as shown by curves.

Split Can Antenna, 575-1,400 mc.

Div. 15	RP-138	Army	AS-180/APT
RRL	M-3301	Navy	AS-180/APT

Used for horizontal polarization in the 575- to 1400-mc frequency range. The antenna consists of a grounded metal can in the shape of a truncated cone having a narrow slot along its full height. It is tuned to a desired 50- to 150-mc bandwidth in its frequency range by means of a variable shorting bar set to give less than 2:1 standing-wave ratio on a 50-ohm line. It is fed by a coaxial cable whose outer conductor is bonded the full length of the inner side of one edge of the slot, and whose inner conductor is tied to the other edge of the slot by a "dog-ear" which minimizes the inductive drop through this lead. The radiation is distributed predominantly forward and to the sides of an aircraft.

411-TM-34 (A. W. Alford, P. L. Harbury). Gives results of preliminary experiments with radiation from split can antennas.

411-IB-46. Brief description and operating instructions, field patterns, and graph of shorting-bar position versus frequency.

Slot Antennas (RP-303, M-6800).

Each of this series of faired-in, nonadjustable an-

tennas for high-speed aircraft consists of a shallow box-like cavity which is energized by a T-shaped feeder. Each operates as a loaded stub in a short length of wave guide. Wide-band performance is obtained by the interaction of the reactances of the T joint, the shorted section of guide forming the back of the cavity, the aperture and skin forming the load. The aperture is covered with a thin sheet of Fiberglas. Input is made through a modified UG-101/U connector mounted in the side of the cavity and connected to the feeder through a tapered section of 50-ohm line. The radiation patterns are polarized perpendicularly to the long dimension of the slot, being wide in one plane and somewhat narrower in the other.

411-166 (D. Lazarus). Describes the structure and characteristics of a slot antenna (M-6804) for the 1,050- to 2,100-mc range.

411-263 (D. Lazarus). Summarizes preliminary development of wide-band slot antenna and discusses operating theory and characteristics. Experimental installations in B-17 and PB4Y2 aircraft are described and transmitter radiation patterns are shown for various M-6800 transmitting antennas. Similar information is given for M-7300 curved slot antennas for XP4M airplane and S-1200 bomb-case jammer. The report is concluded with a brief account of experiments with loaded slot antennas.

411-TM-82 (H. C. Singleton). Brief Description, specifications, characteristics, sketch and photos of assembly, field patterns of dual dipole and reflector, 90-150 mc, ground-based.

Div. 15	RP-279	Army	AS-49/TPT-1
RRL	M-2508	Navy	AS-49/TPT-1

Used with APT-1, APT-3, AM-14/APT for vertical or horizontal polarization, depending upon orientation. Assembly consists of two dipoles fed in phase, each having a corner-type reflector and being adjustable in length to cover the frequency band. Its dimensions are approximately 6 x 11 x 4 ft, with weight of 208 lb. Employs M-2503 conversion unit to feed dipoles in phase and uses M-2504 transformer unit to connect two assemblies in multiple.

411-TM-83 (H. C. Singleton). Same as 411-TM-82 except as regards modifications for higher-frequency range. Dual dipole and reflector, 150-210 mc, ground-based.

Div. 15	RP-279	Army	AS-50/TPT-1
RRL	M-2511	Navy	AS-50/TPT-1

Used with APT-1, AM-18, APT. Equipment is similar to M-2508, except as modified to cover higher-frequency range. Employs M-2509 conversion unit to feed dipoles in phase and M-2510 transformer unit to connect two assemblies in multiple. Uses same connecting cables as M-2508.

411-IB-70. Illustrated description and preliminary instructions for installation, adjustment, operation, and maintenance, with field patterns and graph of standing-wave ratio of dipole and corner reflector, 460-720 mc.

Div. 15	RP-138	Navy	AS-71/SPT-2
RRL	F-3701		

Used with APT-2, APT-5, APQ-9, UPT-T1. The range is covered by adjusting the lengths of the dipole arms for the desired frequency. The entire band can be covered in five settings. Adjustable members are protected from the weather by a waterproof sleeve. Antenna can be used with an input power up to 75 w and has a gain of about 10 db in the maximum direction. Polarization is in the direction of the axis of the dihedral angle and is adjustable by rotating the antenna and reflector assembly.

TMR-57. Brief discussion, chart of dipole length versus frequency, parts list, constructional drawings.

TMR-57A. Drawings for protective sleeve and information on dipole adjustment.

411-TM-78 (H. C. Singleton). Discussion of salient features, field patterns, chart of dipole length versus frequency, drawing and photo of assembly of dipole and corner reflector, 175-550 mc.

Div. 15	RP-138	Army	AS-263/UPT
RRL	F-3903	Navy	AS-263/UPT

Used with APQ-2. The operation depends upon the adjustments of the length of the dipole in the corner reflector. Several settings of each of these parameters are necessary to cover the frequency range with a standing-wave ratio of less than 2:1. The field pattern is practically independent of polarization. The antenna gain is approximately 10 db.

TMR-92. Brief description, parts list, photo, constructional drawings for F-3903.

TMR-92A. Brief description, photo, parts list, and construction drawings for F-3903 ship-borne directional antenna system designed primarily for use with F-3800 practice jammer.

411-IB-58. Illustrated description and preliminary instructions for installation, adjustment, operation, and maintenance, including antenna patterns and graph of standing-wave ratio versus frequency of dipole and corner reflector, 700-1,300 mc.

Div. 15	RP-138	Navy	AS-145/SPT-6
RRL	F-3702		

Used with SPT-6 and APT-5. Consists of an ad-

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justable dipole, provided with a balanced matching section, mounted in a corner reflector. An adjustable mounting bracket and calibrated scale permit setting the antenna and reflector assembly at any desired orientation in a single plane. The frequency range is covered in three settings of dipole length.

End-Fed Balanced Antennas, 85-800 mc.

Div. 15	RP-138	Navy	CAKZ-66 AJA
RRL	M-2901		CAKZ-66 AJB
	M-2902		CAKZ-66 AJM
	M-2903		CAKZ-66 AKJ
	M-2904		CAKZ-66 AKL
	M-2906		CAKZ-66 AKM
	M-2907		CAKZ-66 AJY
	M-2908		CAKZ-66 AJR
	M-2909		CAKZ-66 AJY
	M-2910		
	M-2912		
	M-2913		

These antennas are designed for use with CXFR, TDY, or SPT-7 transmitters without adjusting the antenna throughout its rated range. M-2901 covers the 350-685 mc range, M-2902 the 645-800 mc range, M-2903 the 175-350 mc range, M-2904 the 85-175 mc range, M-2906 the 143-275 mc range, M-2907 the 265-540 mc range, M-2908 the 450-820 mc range, M-2909 the 800-1,400 mc range, M-2910 the 810-1,385 mc range with TDY, M-2913 the 810-1,385 with the SPT-7 transmitter. All are designed for waterproof mounting on a mast. Each consists of a dipole, untuned reflector, and converter from unbalanced to balanced transmission line. The patterns for vertical polarization in the horizontal plane are broad enough to allow for changes in the ship's course with small reduction in signal toward the target. The patterns for vertical polarization in the vertical plane are wide enough to allow for moderate roll of the ship and yet narrow enough to prevent undue waste of energy at angles removed from the horizontal.

411-TM-140 (E. L. Bock). Illustrated description of M-2903 with graphs of standing-wave ratio versus frequency and field patterns for various reflector spacings.

411-218 (G. Stavis). Describes the mechanical construction and the electrical performance of the M-2914 r-f relay for remote switching of antennas. The report includes voltage standing-wave ratio curves showing effects of two types of right-angle connectors on the electrical performance of the relay.

411-210 (E. L. Bock). Gives design information and dimensions for building M-2900 corner-type antennas covering 140- to 1,400-mc range by means of four antennas. Each is fundamentally a sleeve dipole in a 135-degree corner reflector. Sleeve and balun impedances are given along with typical curves of standing-wave ratios and measured field patterns.

411-TM-134 (C. Driscoll). Description, photos, measured field patterns and graphs of energy distribution and standing-wave ratio under various experimental conditions of high-gain antenna, 1,500-3,000 mc (RP-138, M-4400). This laboratory model typifies a suitable ground-based antenna to be used with a jammer operating above 1,500 mc. The model produces vertically polarized radiation in a 30-degree fan-shaped pattern in the horizontal plane and 6 degrees in the vertical plane. It gives a gain of 23.4 db at 1,500 mc and 27.7 db at 3,300 mc. The antenna consists of an 8-ft cylindrical parabolic reflector fed by a 3-ft horn. A similar antenna with a height of 5 ft or less may be adapted for ship-borne use in the 10-cm region.

411-TM-143 (W. G. Wadey). Brief description illustrated by sketches, with statement of pattern characteristics of search antennas, 3,000-6,000 mc.

Div. 15	RP-107
RRL	R-1004
	R-1022

Used with AN/APR-5A receiver aboard naval vessels for searching in the 5- to 10-cm range. R-1022 is a biconical horn feeding a separate coaxial cylindrical line joined to a wave guide by a continuous transformer; it is used for reception of vertically polarized waves. R-1004 consists of the open end of a toll ticket tubing wave guide covered with a hood to keep out the weather; it is used for horizontal polarization. Each has a broad pattern in the horizontal plane with a single null, the desired form, since the antenna will be installed on either the forward or aft side of the mast at or below the level of the yardarm.

411-101 (C. Driscoll). Illustrated description, suggestions for installation and operation, field patterns, and graph of standing-wave ratio of high-gain antenna, 2,880-3,310 mc (RP-303, M-4701). This horizontally polarized antenna was used to test the jamming effectiveness of a klystron tube transmitter having 10-w output (Q-1100). It has a gain of about 23 db and its sharp radiation patterns are suitable for screening a destroyer at 5,000 yd against a microwave medium-power radar system. It consists of a horn-fed cylindrical parabolic reflector with a swivel base permitting 360-degree rotation and about 20-degree variation in elevation. The horn is fed by a wave guide which is fed by a

length of RG-14/U cable from the transmitter. A matching adjustment between the cable and guide is provided by a movable plunger at the end of the wave guide. A pair of sights attached to the reflector and aligned with the axis of the radiation pattern provides accurate sighting control of the radiation direction of a visible target.

411-18 (J-400, RP-107) (R. Silliman). Gives results of measuring the input impedance versus frequency characteristics of various models of *cone antennas*. The data are presented by curves plotted in terms of driving-point impedance versus overall length in wavelengths. Curves are also plotted for the coefficient of reflection and standing-wave ratio (see 411-23) of one of the models. The general conclusions are that the bandwidth of a cone antenna depends upon the allowable degree of terminal mismatch, being less for transmitting than for receiving. For a 0.17 reflection coefficient (R) a bandwidth of 3 to 1 is obtainable from a 70-ohm line or 1.5 to 1 from a 50-ohm line. A bandwidth of at least 4 to 1 is obtainable from either type of line for $R = 0.33$.

411-34 (MJ-2100, RP-107) (C. M. Daniell). Gives results of measurements of impedance characteristics of *cylindrical antennas* varying from 10 to 256 in ratio of length to diameter and from ⅛ to 1 wavelength in length. The data are presented in the form of curves from which it is concluded that the effect of decreasing the ratio of length to diameter is to smooth the resistance and reactance curves, with relatively small effect on the resistance at the quarter-wave and three-quarter-wave resonance points and large effect at half-wave and full-wave resonance. The divergence between the electrical and physical lengths is found to increase more rapidly for long than for short antennas and for ratios of length to diameter of less than 30 to 1.

411-TM-34 (M-2700, RP-303) (A. Alford, P. L. Harbury). Reports on preliminary experiments on radiation from *split can antennas*. The antennas were metal cylinders (30 cm long and of various diameters) split lengthwise along one side. When one end of the antenna is connected to the ground plane it is energized by a single coaxial line connected either to the top or the center of the can. When the antenna is raised above the ground plane by small insulators it is energized by a balanced feed (conversion unit) connected to the bottom of the can. Test results tend to substantiate the tentative theory that the two edges of the lengthwise split constitute the two wires of a transmission line, whilst the effect of the rest of the can represents that of a number of loops shunted across the lines. Because most of the energy is radiated from these "loops," the radiation is polarized in a plane perpendicular to the lengthwise axis of the can. An antenna can be energized to give either vertical, horizontal, or circular polarization. When the shunts are $\lambda/4$ in length, the resonant frequency is determined solely by the length of the can.

411-23 (G-400 and J-302, RP-107 and -138) (E. Fubine, P. J. Sutro, R. F. Lewis). Gives methods for calculating the characteristics and *performance of wideband matching line sections* in series at frequencies other than those for which they were designed. The sections investigated include single and double quarter-wave (which are found to cover very much wider bands than are usually assumed) and half-wave sections (for matching a load at two frequencies). The concept of "ideal load" is introduced—that is, the load which varies with frequency in such a way as to compensate exactly for the frequency characteristic of the transformer. Thus the matching problem is reduced to that of finding the matching transformer whose ideal load most nearly approximates the actual load to be matched. In terms of this concept, the case of a transformer composed of a single section of line is considered in detail, and plots of ideal load as a function of frequency are included. A simple formula is given for the reflection coefficient in terms of the ideal and actual loads. An appendix discusses the factors which limit the acceptable mismatch in transmitting and receiving antennas.

411-TM-24 (G-1000, RP-107) (Donald Foster). Explains and proves the validity of a method for *calculating the pattern of an antenna*. The method is based upon choosing as an origin of radiation some point, if it exists, at which the equivalent current phase is independent of direction, and regarding the entire antenna as an array of such specially located point radiators. The Poynting flux is then readily calculated from the magnetic vector potential. Examples are given for a dipole consisting either of straight nonresonant elements or of segments one-quarter wave in length.

411-TM-42 (G-1000, RP-107) (Donald Foster). Describes an *airborne lobe-switching antenna* to locate enemy transmitters of unknown frequency. The antenna consists of a small horizontal Vee mounted with its open end toward a vertical reflecting plate. The pattern usually has one lobe pointed backward toward the driving point. The lobe is switched to either side of a vertical plane normal to the reflecting plate by interchanging the driving point and the terminating resistance. Satisfactory lobe-switching patterns are obtained for two ranges of the ratio of a side of the Vee to the wavelength.

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These ranges are approximately 0.4 to 0.6 (for which the radiation resistance is nearly constant at 90 ohms) and 0.12 to 0.35 (for which the radiation resistance varies from 5 to 72 ohms as a linear function of the frequency). The report contains a number of directional patterns calculated by a formula which is illustrated by a sketch.

411-TM-123 (G-1000, RP-107) (Donald Foster). Gives general equations describing the salient features of *loop antennas* in the shape of a circle or of large polygons having a center of symmetry. Consideration is given to unattenuated traveling current waves, standing waves, and uniform current distributions. Various ways are shown for driving polygons or circles with substantially uniform current. It is suggested that similar directivity patterns and polarization characteristics might also be obtained by means of wave guides terminated by annular horns. The solution of the problem of the circular antenna with uniform current is treated in detail, giving directivity and radiation-resistance graphs. With uniform current and less than two wavelengths in the perimeter, the circle or polygon seems to have possibilities as a transmitting antenna for horizontally polarized waves. At high frequencies or with large loops the vertically mounted circular antenna may be used to transmit in a particular direction with either horizontal or vertical polarization, depending upon whether the normal to the loop lies in the same vertical plane or the same horizontal plane as the target. Rotation of the normal to the circle around the direction of the target would rotate the direction of polarization around the ray at the same speed.

411-192 (G-1000, RP-107) (D. Foster). Theoretically determines an *optimum directivity pattern for search antennas*. The determination is based upon permitting the maximum area to be inspected per unit time of search with uniform quality and upon the probability of detecting the presence of an operating radar in that area. The resulting pattern has (1) a forward bulge which is sufficient to detect operating radar close to the line of flight and (2) a forward slanting region having a constant minimum transit time.

411-158 (G-608, RP-318) (D. Foster). Describes and analyses two methods for locating a rotating beam transmitter by means of *continuously rotating DF antennas* with azimuthal scope presentation. Either method overcomes the difficulty caused by the false-direction indication due to variation of field strength of the receiver. One method merely requires the selection of the largest of a number of curves (eight are typical) drawn on the scope by a single receiving antenna having a much higher rotational speed than the transmitter. The other method requires two DF antennas having mirror-image directivity diagrams and rotating at the same speed in opposite directions. True direction is then found by bisecting the angle between the two false directions that are indicated when the antennas are so adjusted in relative angle that their outputs trace identical curves on the scope.

411-119 (A. W. Alford, I. G. Clarke). Presents five semiempirical equations for determining the *power gain and beamwidth of high-gain antennas*. The formulas for gain are in terms of known (1) aperture and operating wavelength, (2) beamwidths, and (3) number of half-wave radiators in a mattress array. The formulas for beamwidth are in terms of known aperture dimensions and wavelengths. Eight numerical examples are given for comparison with measured values.

411-212 (M-1037, RP-306) (D. Lazarus). Instructs on methods for adapting AS-161/ART and AS-97/ART *whip antennas as radiators* horizontally polarized in the 75-mc region. Two whips are cut to 40-in. lengths, bent at a 45-degree angle, and installed (properly phased) on opposite sides of the fuselage toward the forward end of a plane. They may also be easily modified for pressurization, if necessary. The report includes test procedure and data which indicate the required broad patterns with maximum radiation forward and below the aircraft.

411-203 (M-7501, RP-481) (J. Margolin) Describes field *modifications of AN-148A* (designed for IFF) to adapt it for interim use as an anti-GL antenna in the 200-mc region. The report includes structural sketches and standing-wave measurements.

411-203A (W-2210, RP-481) (M. P. Klein). Gives results of flight tests for determining the *radiation characteristics of modified AN-148A* antenna. The characteristics appear to be satisfactory for use in jamming horizontally polarized GL radars in 200-mc region.

411-202 (M-7407, RP-299) (H. Clark and E. F. Shaw). Presents 59 graphs to be used in determining *optimum height of jamming antennas*. In most of the graphs the field strength in volts per meter is plotted against the range of the enemy ship in yards. Calculations are based on jammer heights of 40, 80, and 120 ft and on enemy radar heights of 80 and 120 ft at frequencies from 200 to 6,000 mc with both vertical and horizontal polarizations. Values chosen for jammer power, antenna power gain, and cable or wave-guide attenuation are given

on each graph. Methods of calculation are explained in the report.

411-242 (C-3303, RP-481) (J. W. Christensen). Describes the rapid method and simple equipment used to obtain *continuous antenna patterns* from small-scale models of whip antennas mounted at different positions on a rotating model of a B-24. Patterns are obtained by photographing polar traces on a plan-position indicator scope having radial deflection and long-persistent screen. Selsyns synchronize the scope's rotational deflection with rotation of the model. The drive mechanism and indicator consist of modified DMB equipment. The method's usefulness is illustrated by conclusions drawn from studying the effects of bending antennas that are usually mounted perpendicularly, thereby minimizing nulls.

411-283 (C-3200, -3500, RP-303) (C. C. Loomis, R. M. Hatch). Describes methods and equipment used in designing two *circularly polarized S-band antennas* for shipboard use. Each was to have a 30-degree elevation pattern centered on the horizontal (to allow for ± 15-degree roll or pitch), one with a 360-degree azimuth pattern and the other with a 90-degree pattern. Since the antennas were to utilize an M-9001 horn, the problems were reduced to designing proper reflectors. These problems and their compromise solution are discussed in detail. Antennas which meet the specifications in some important respects are described.

759-1 (G. Sinclair) Gives *patterns of cone antenna models* of various sizes mounted on a circular plate. These measurements are preliminary to the measurements for cones mounted on aircraft and show various distortions which are briefly discussed.

(October 29, 1942)

759-2 (G. Sinclair). Gives radiation *patterns of a cone antenna* at two locations on a B-17E. Most of the energy is found to be vertically polarized and there is no evidence of pronounced structural resonances in the aircraft.

(November 22, 1942)

759-3 (G. Sinclair). Gives *patterns of cone antennas on a B-24* and suggests optimum locations for 100- to 300-mc and 300- to 1,000-mc antennas to be used for reception of signals of unknown polarization.

(December 20, 1942)

759-4 (G. Sinclair). Gives *patterns of a dipole on AT-11* aircraft at 110 mc for three mounting locations.

(December 28, 1942)

759-5 (G. Sinclair). Gives *patterns of horizontal stub antennas* projecting from the nose of an AT-11. Measurements simulating 200 mc were made for a quarter-wave stub, a three-quarter stub, and a quarter-wave stub with disk.

(January 21, 1943)

759-6 (G. Sinclair). Gives *patterns for 50-ohm cone mounted on a disk* for simulated operation at 250, 400, and 1,000 mc.

(January 23, 1940)

759-7 (G. Sinclair). Gives *patterns of an array for SCR-587 on B-17F.* The report tells how the array is phased.

(February 20, 1943)

759-8 (G. Sinclair). Gives *patterns of stub antenna pairs* for RC-164 lobe switching on B-17F at 115-130 mc.

(March 17, 1943)

759-9 (G. Sinclair). Briefly discusses *patterns of antennas for Gymnast,* including those given in 759-7 and 759-8, and predictions of those for various search receivers in 75- to 1,000-mc range.

(March 25, 1943)

759-10 and **759-11** (G. Sinclair, R. B. Jaques). Gives *patterns for antennas mounted on Hairy Butterfly.* The antennas are dipoles and loops of various sizes mounted at various locations.

(May 15, 1943) (June 11, 1943) (June 25, 1943)

759-12 (R. B. Jaques). Gives *antenna patterns of special loop on A-29* bomber for 200 mc.

(July 24, 1943)

759-13 (R. B. Jaques). Gives *patterns of vertical antennas on B-17 and B-24* bombers for 35 mc.

(August 2, 1943)

759-14 (R. B. Jaques). Gives *patterns of a short, wide-band antenna* for 200- to 500-mc range.

(August 2, 1943)

759-20 (RP-137) (E. A. Jones, G. Sinclair). Presents *antenna radiation patterns for Albatross I* project. Measurements were made on M-1203, M-801, and a quarter-wave stub installed on the equivalent of a PB4Y-2.

(February 25, 1944)

759-21 (RP-269) (R. B. Jaques). Presents *reflection patterns of B-24 at 100 mc,* based on data taken on a scale model of the bomber.

(March 18, 1944)

759-22 (RP-269) (R. B. Jaques). Presents *reflection patterns of B-17E at 100 mc,* based on data taken on a scale model of the bomber.

(March 18, 1944)

759-23 (RP-137) (E. A. Jones). Presents *antenna radiation patterns for HS-293.*

(June 20, 1944)

759-24 (E. W. Vaughan, N. Kennedy). Gives constructional data for a *square root amplifier* designed to drive a square-law recording indicator so that the deflection of the pen is proportional to the square root of the amplifier input voltage.

(May 29, 1944)

759-26 (RP-137) (E. A. Jones). Presents *radiation patterns for antennas on PB4Y-2,* including M-1203, M-801, stub mast, IFF whip, and v-h-f whip. The models were 1/10 and 1/20 scale.

(September 10, 1945)

759-27 (RP-137) (E. A. Jones). Presents *radiation patterns for antennas on P4M,* including AT-49/APR-4 and AN/APX-8.

(September 1, 1945)

759-28 (RP-137) (E. A. Jones). Presents *radiation patterns of antennas on Ferret C-1* project, including an AT-43/APT stub and two AS-97/ART stubs fed as a two-wire fan and a three-wire fan.

(September 10, 1945)

759-29 (RP-137) (E. A. Jones). Presents *antenna radiation patterns for 1,000 mc on the SB23.* The AS-133/APX-6 was mounted at three locations in an effort to determine the best location. A pattern calculated by rap-optics theory has the same number of lobes as the model pattern, but the lobes have different angular positions.

(September 13, 1945)

759-30 (RP-269) (K. P. Yates, P. C. Wright). Describes experimental procedures used and gives the results obtained for *reflection measurements on target tow cable* designed at RRL to be antiresonant at 10- to 11-cm wavelengths. Using data obtained from tentatively designed samples, an improved antireflective cable was designed, tested, and found to give good performance.

(August 13, 1945)

759-31 (RP-137) (D. R. Rhodes, E. C. Jordan). Discusses the *modeling of slot antennas* for the measurement of patterns. Preliminary investigation of calculated and measured patterns indicate that the patterns of slot antennas are as predictable as those of any of the more common types.

(October 3, 1945)

759-32 (RP-427) (H. Heil, E. Jordan, D. Cleckner). Discusses the *modeling of ship-borne antennas* for the measurement of patterns, taking into account the effect of the sea on the pattern. Comparison of theoretical curves with experimental data indicates that the pattern is a function of distance, that the total unattenuated pattern closely resembles that given by a model over a highly conducting ground screen, and that the fields of a dipole account for the effect of finite conductivity upon the pattern at any particular distance. Patterns obtained with a model sleeve antenna for 18 mc showed reasonable correlation with measurements on the prototype. A terminated ground plane of reasonable size is found to be satisfactory for measuring patterns using wavelengths less than 50 cm.

(October 16, 1945)

759-33 (RP-269) (K. P. Yates, P. H. Nelson). Describes a *c-w method for measuring reflection patterns* from scale models of aircraft, RCM decoys, missiles, and other bodies by means of a transmitting and receiving system which discriminates between the transmitted and reflected signals. The measuring system is essentially a directional antenna array mounted within a wave guide with horn so that the array rejects energy transmitted through the guide toward the model and absorbs the signal reflected from the model. The method depends upon the principle of electromagnetic similitude whereby the reflection of 2,000-mc energy from a 1/20th scale model, for example, is equivalent to that of 100-mc energy from the prototype. The report contains sample patterns which partly duplicate those listed herewith for specified measurements of reflections from bombers, corner reflectors, and tow cables. The report also describes the use of models in studying radar echoes from mortar shells and rockets.

(October 18, 1945)

759-34 (RP-137, -269, -427) (G. Sinclair). Summarizes *Ohio State University research* for Division 15 of the Office of Scientific Research and Development, including work done on communications jamming equipment, airborne and ship-borne antenna radiation patterns, and aircraft echoing areas.

(October 16, 1945)

778-5 (S. A. Schelkunoff, W. C. Babcock). Describes a proposed *broad-band airborne antenna system* and a method for broadening the band of an antenna by means of equalizing circuits. The proposed system consists of two parallel spaced wires (one insulated and the other grounded) running from tail to wing tips and fed by a transmission line running back to the tail. Analysis shows that they should provide a practical antenna for barrage jamming at lower frequencies. The band-broadening method is illustrated by the design of networks to use with two whip antennas over the 38- to 48-mc band.

(January 26, 1943)

867-1 (RP-261) (R. Serrell). Correlates work done at CBS and Ohio State University Research Foundation on design of a suitable *antenna system*

for Moth. Preliminary measurements at 122 mc indicate that approximately the same power is delivered by a loop and half-wave dipole. The report includes drawings and radiation patterns for two proposed dipoles with horizontal polarization and one with vertical polarization.

(November 1943)

867-5 (RP-261) (J. A. Nelson). Gives graphs showing the *input impedance of long-wire antennas* having a cylindrical cross section. The general conclusions are that the antennas are predominantly capacitive with a mean reactance of about 30 ohms and that the variations in resistance and reactance become smaller as the electrical length of the antenna increases and as the physical length-diameter ratio decreases. Measurements were made for electrical lengths varying from one-half wavelength at 100 mc to five wavelengths at 1,000 mc.

(January 14, 1944)

867-7 (RP-261) (R. Serrell). Describes *stub antennas with series matching sections* suitable for mounting on the B-24 and for covering the 34- to 38-mc, 38- to 42-mc, and 42- to 50-mc bands with a standing-wave ratio in a 50-ohm feed line not smaller than 0.5.

(April 1944)

867-10 (RP-261B) (E. C. Hayden). Describes an *electromagnetic model of the ocean* to be used in obtaining patterns of antennas mounted on ship models. The ocean surface is represented by a large bronze screen surrounded by "Uskon cloth" absorbing screens to prevent reflections at the boundaries of the model. Test measurements of patterns indicate that the model is satisfactory for most measurements.

(February 1945)

895-1 (RP-260) (P. S. Carter). Gives the measured impedance characteristics and radiation pattern of a *sleeve antenna* consisting of the outer surface of a coaxial line and the projection of the inner conductor. The impedance characteristic is found to be somewhat broader than that of a dipole. The resonant resistance is about 100 ohms. A frequency band of one octave can be covered with less than 50 per cent reflection. The report also states that the *use of steel for antenna units* does not introduce appreciable losses compared with the use of copper.

(July 14, 1943)

859-2 (RP-260) (R. S. Wehner). Tells of improved impedance characteristics resulting from using the *sleeve antenna* principle with a corner reflector, a fan, and an inverted L. Use in a corner reflector yields good directivity combined with bandwidths ranging from 10 per cent at 5 per cent reflection to 50 per cent at 30 per cent reflection.

(September 9, 1943)

859-3 (RP-260) (P. S. Carter). Gives an approximate formula for estimating the *power limit of airplane antennas* and gives a curve sheet of values for quarter-wave antennas at 40,000-ft altitude in rainy weather. The values for a free-space dipole are about twice those shown by the curve and are greatly reduced as the length of the antenna is reduced below one-quarter wavelength, being proportional to the radiation resistance for a particular length.

(August 12, 1943)

895-10 (RP-260) (P. S. Carter, R. S. Wehner). Gives results of *antenna tests* and finds that a sleeve antenna is useful over a wider band than is a helical antenna, dielectric cone, dielectric cylinder, or half folded dipole. A quarter-wave stub mounted on a B-24 matches a 50-ohm line at 40 mc, is good for a band of several megacycles, and distributes radiation satisfactorily.

(December 22, 1943)

895-11 (RP-260) (P. S. Carter). Derives formulas and gives computed radiation patterns for dipole and loop *antennas on cylindrical fuselages.* Theoretical patterns are computed for the antenna axis parallel, radial, and circumferential to the axis of the cylinder. Some patterns have been checked experimentally and indicate radiation paths of antennas mounted on a fuselage in positions where the wings have negligible effects.

(December 24, 1943)

895-15 (RP-260) (R. S. Wehner). Describes two methods for determining the constants of transmission line matching sections and applies them to the *synthesis of broad-band antenna matching sections.* One is a graphical method for use with antennas which are flat enough to be matched by a simple series line section. The other is an approximate analytical method that is applicable to highly reactive antennas.

(March 6, 1944)

895-16 (RP-260) (P. S. Carter). Presents two charts which give values for the *power limits of trailing wire antennas.* The curves are based upon an altitude of 40,000 ft in wet air. One chart gives the safe minimum wire size for quarter-wave antennas for power ranging from 10 to 1,000 w. The other chart gives similar data for antennas varying in length from one-twelfth to one-half wavelength.

(March 10, 1944)

895-17 (RP-260) (P. S. Carter). Discusses the

SECRET

effects of antenna coupling upon pattern distortion change in input impedance and reaction between transmitters. Data are given to permit selection of locations for two antennas to have a degree of coupling below any specified value. The theory provides partial prediction of the interaction for a system of four antennas. Tests are suggested for determining the maximum degree of coupling allowable before serious trouble develops from the reaction between transmitters operating at nearly the same frequency.

(April 11, 1944)

895-21 (RP-260) (N. E. Lindenblad). Gives preliminary results of *measurements on a 1,200-ft wave antenna* over Rocky Point soil and compares them with results obtained with vertical radiators. For the major portion of the 200- to 8,000-kc range the wave antenna shows greater than a 12-db gain in the transmitting direction. The gain may be increased by paralleling of wires. Except for ground conditions corresponding to salt marsh, the use of wave antennas for transmitting seems to be pertinent and attractive.

(May 2, 1944)

895-23 (RP-260) (W. A. Miller). Gives preliminary results of *measurements on 1,200-ft wave antennas* over Tobyhanna, Pennsylvania, soil, which is wet, heavy loam. The wave antenna is found to have a gain of 10-12 db over a 30-ft vertical antenna at 200-2,000 kc.

(June 20, 1944)

895-24 (RP-260) (R. S. Wehner). Gives the impedance characteristics for a *broad-band inverted-L antenna* which has been modified so as to have two-thirds the height of a conventional quarter-wave stub and so as to be conveniently matched to a 50-ohm line over frequency bands approaching 60 per cent in width. The modification is a sleeve extension of the outer conductor of the feed line, which has a much greater diameter than the horizontal conductor of the antenna. The characteristics and the radiation pattern indicate that the antenna is practical for use on aircraft at frequencies less than 150 mc.

(July 20, 1944)

895-27 (RP-260) (R. F. Franklin). Gives preliminary results of *measurements on wave antennas over sandy soil.* The antennas tested were one-, two-, and four-wire, 1,200 ft and 2,250 ft long, and one- and two-wire, 3,600 ft long, over a 200- to 2,000-kc range. The tests indicate better performance over sandy soil than over wet, heavy loam. Except for high frequencies the wave antenna performance is inferior to that of a vertical quarter-wave balloon-supported antenna.

(August 28, 1944)

895-29 (RP-352) (R. S. Wehner). Describes a simple coax-fed V dipole *u-h-f antenna for horizontal polarization.* Impedance and pattern data are presented to indicate that the antenna may be useful over frequency bands approximately 35 per cent wide. An assembly drawing is given for one of a series of four to cover a combined 500- to 1,500-mc range.

(October 19, 1944)

895-31 (RP-260) (P. S. Carter). Discusses the radiation characteristics of *circular loop antennas at high frequencies.* Formulas are derived and curves are given to show radiation resistance versus loop size and also the voltage induced in a receiver loop. A few patterns are also given to show the distribution of radiation from loops of one wavelength and one-half wavelength circumference. The curves cover loops of any size having the natural approximately sine-wave current distribution.

(January 10, 1945)

895-32 (RP-260) (N. E. Lindenblad). Describes and gives test measurements of *wide-band slot antennas* having a 30 per cent bandwidth when accepting a 2:1 standing-wave ratio tolerance. Such performance is obtained without the aid of compensating transmission line elements.

(March 26, 1945)

895-33 (RP-260) (R. S. Wehner). Describes the graphical *computation of two-element broad-band matching sections* (2:1 standing-wave ratio for bandwidth greater than 30 per cent) by means of two charts. The charts solve the problem of matching a series resonant antenna (resonant resistance greater than 2-5 ohms) to a 50-ohm transmission line by means of an L-type circuit consisting of an antiresonant shunt section followed by a series transformer.

(February 2, 1945)

895-35 (RP-260) (R. S. Wehner). Describes an u-h-f *zero-drag aircraft antenna* consisting of a sleeve antenna mounted axially in a semicylindrical cavity recessed into the skin of a plane. The physical dimensions are small enough to be practical at frequencies higher than 300 mc. The impedance and pattern characteristics suggest its use for altimeters, guided missiles, tail warning, and IFF, using either vertical or horizontal polarization.

(January 15, 1945)

940-5 (C. R. Burrows). Presents and describes charts for determining the factors to be used in the design of *admittance transforming networks,* such

as are used in matching the plate circuit of a vacuum tube to an antenna. A pi network is used to transform one complex admittance into another.

966-5 (W. C. Babcock). Gives formulas and curves for approximate values of the *average characteristic impedance of fan dipoles.* The computed values are found to average about 10 per cent higher than values determined by impedance measurements.

(May 24, 1943)

966-8 (W. C. Babcock). Gives approximate formulas and curves for the average *characteristic impedance and multiwire cylindrical cage dipoles.*

(July 1, 1943)

966-14 (S. A. Schelkunoff). Compares the measured and theoretical *impedance characteristics of cylindrical radiators* by means of a series of curves which show fair agreement between theory and experiment.

(June 28, 1943)

966-15 (W. C. Babcock). Consists of charts and comments on computed values for the *input impedance of hollow cylindrical dipoles* with characteristic impedances varying from 250 to 600 ohms. For characteristic impedances less than 300 ohms it is noted that the input impedance tends to flatten out over a rather broad band between the first and second antiresonant frequencies and that it is closely resembled by the input impedance of a 60-degree conical dipole.

(August 25, 1943)

966-38 (RP-410) (W. C. Babcock, E. O. Bernard, C. R. Eckberg, M. C. Francis). Describes the *stingaree trailing coaxial dipole* airborne antenna designed for use against German tank communications in the 27- to 33-mc band and 40-mc region. The antenna consists of two hollow radiators each about 1 in. in diameter and one-quarter wavelength in length, with a coaxial feeder passing through one of them in order to reach the center of the dipole. The 50- to 100-ft coaxial feeder serves as a towing line and prevents any serious distortion of the radiation pattern by the plane. This antenna has a 20 per cent bandwidth over a 2:1 standing-wave ratio and may be used with many different types of planes. Vertical polarization is provided by a 30-lb weight at the end of the antenna and horizontal polarization, by a small wind sock. The report gives results of preliminary tests.

(December 9, 1944)

966-47 (RP-410) (M. E. Campbell, C. R. Eckberg, M. C. Francis). Gives *stingaree antenna patterns* at 30 mc, supplementing those in 966-38. Field tests indicate that the antenna can be satisfactorily towed and that pattern shape is not materially affected by the length of the cable outside the aircraft. (Length of 20-40 ft recommended for 30 mc.) The vertically poled pattern is reasonably circular when aircraft is less than 10 degrees above the horizon. At higher angles the energy is greater in front of the aircraft.

(March 15, 1945)

1045-6 (RP-992) (R. F. Lewis, G. H. Klemm). Constructional data on a *sleeve antenna* for receiver-transmitter use in the 350- to 400-mc range. The antenna is designed for vertical polarization when mounted on the under surface of an aircraft. An included curve sheet shows standing-wave ratio to 63-ohm line to be 2:1 for 350-410 mc, 3:1 for 210-430 mc, and 10:1 for 180-520 mc.

(April 17, 1944)

1045-7 (R. F. Lewis, G. H. Klemm). Constructional data on *sleeve antenna* for use with a 150- to 450-mc receiver. The antenna is designed for vertical polarization when mounted on the under side of an aircraft. An included curve sheet shows standing-wave ratio to 63-ohm line to be 2:1 for 305-360 mc, 3:1 for 190-380 mc, and 10:1 for 150-450 mc.

(April 17, 1944)

1305-1 (RP-382) (L. K. Findley). Gives preliminary measurements for *patterns of antenna on model of German Hs-293 glider bomb.*

(April 24, 1944)

1305-10 (RP-402a) (N. E. Klein). Describes the *CLU-24314 antenna switching unit* for selectively connecting a coaxial input cable to any one of eight coaxial antenna feeders.

(April 17, 1945)

1305-19 (RP-402b) (N. E. Klein). Describes a remote-control *antenna transfer switch* for connecting a single coaxial line with any one of six other coaxial lines. A similar manually controlled model is also mentioned.

(August 31, 1945)

1305-TM2 (O. H. Schmidt). Describes an *r-f dummy load* having a fixed resistive impedance over a 500-mc range and capable of dissipating 1,500 w. The load surrounds the end of an r-f cable and consists principally of a brass block containing a slot through which salt water is circulated at a constant rate. Rise in temperature determines the amount of power dissipated.

(August 31, 1945)

6.5 COAXIAL CABLE, WAVE GUIDES, AND FITTINGS

411-TM-30 (W. W. Salisbury). Analyzes the effect of copper losses (due to skin effect) on the *group velocity of radio waves in a coaxial line* and concludes that the formula should be

$$V = \frac{1}{L_o C_o \left(1 + \frac{\pi}{Q_o}\right)}$$

where $Q_o = \frac{\omega L}{R}$.

411-TM-130 (G-400, RP-107) (P. J. Sutro). Presents and compares the accuracy of three formulas for computing the *characteristic impedance of a shielded balanced line* composed of two inner conductors symmetrically placed within a cylindrical shield. The most convenient formula is found to be

$$Z_0 = \frac{120}{\sqrt{e}} \cosh^{-1}\left[\frac{1}{x} \cdot \frac{1 - y^2(1 - x^2)}{1 + y^2(1 - x^2)}\right],$$

where e = dielectric constant of the dielectric filling the line, $x = r/s$, and $y = s/R$, with s = distance from center of shield to center of one conductor, r = radius of one conductor, and R = radius of shield. This formula is sufficiently accurate for most purposes if x and y are not too large. It should be noted that x and y are always less than unity.

411-TM-85 (G-409, RP-107) (P. J. Sutro). Derives equations for the frequency *bandwidths of resonant-line sections* with and without resistive loads. The terminating reactance with which a section is resonated is either in parallel or in series with the section and the generator. Equations are also derived for the change in frequency band produced by a change in the mode of resonance, whether the mode be shifted by changing the physical length of the section or by changing the frequency. In an appendix the equations are used to determine the characteristic impedance (Z_c) which provides optimum bandwidth from an oscillator consisting of a section of coaxial line resonated with the interelectrode capacitance of an oscillator tube connected in parallel with a load resistance. For first-mode operation the relation between the bandwidth and Z_c is given by the equation.

$$Q = R\omega C\left[1 + \frac{1}{(2\omega^2 C^2 Z_c^2)}\right],$$

where Q = resonant frequency/frequency bandwidth,
R = total resistance seen at resonance,
$\omega = 2\pi f$,
C = interelectrode capacitance of oscillator tube.

In practical cases an increase in Z_c is thus seen to increase the first-mode bandwidth. A shift to a higher mode, however, is mathematically found to cause a decrease in bandwidth. Consequently, if the oscillator is to be operated in more than one mode, it is generally advantageous, in contrast with usual practice, to make Z_c as small as possible. This provides a more uniform bandwidth over all modes and extends the frequency range of the first mode while increasing the bandwidth in the higher modes.

411-TM-132 (G-409, RP-107) (P. J. Sutro). Considers the theory of *mode separation in a standard coaxial oscillator* using two sections of coaxial transmission line as resonant circuits. From calculated graphs it is shown that the mode separation (the difference in the setting of one of the sections for the two modes) increases with the difference between the products of terminating capacity and the characteristic impedance for the two sections. The mode separation is seen to vary quite slowly as a function of frequency.

411-TM-118 (M-100, RP-306) (C. M. Daniell). Details procedure in measuring the relative *power supplied to a load through a coaxial transmission line*. The method consists of inserting a probe voltmeter into notches cut in the line at small intervals compared to the wavelength in order to determine the maximum and minimum crest voltages along the line. Then the power in watts is proportional to $E_{\max} E_{\min}$.

411-255 (A-4300, RP-405) (J. C. Turnbull, J. R. Duggan, R. W. Green). Reviews *measurements on wide-band coaxial lines* preliminary to development of line to transmit 1 kw with minimum standing-wave ratio and attenuation for frequencies in the range from 500 to 2,500 mc. Tests showed that beaded lines are unsatisfactory because of reflections. The best line for low reflection and attenuation appears to be a longitudinally supported line using ½-in. polystyrene tubes to support the inner conductor.

411-123 (R-1000, RP-107) (W. G. Wadey, T. E. Moore). A plotted curve showing the results of measurements of the *attenuation of RG-21/AU cable*. Over the range from $\lambda = 3$ cm to $\lambda = 15$ cm, the data lie close to the curve $a = 3.8\lambda - \frac{2}{3}$. No change in the loss was observed when the cable was handled.

411-TM-17 (Z-801) (L. T. Slocum). Contains curves showing the *power loss in* various lengths of *Federal B-45 cable* at frequencies from 100 to 3,000 mc for a 1:1 standing-wave ratio.

411-237 (U-1600, RP-472) (J. G. C. Swinney). Summarizes RRL accomplishments in the design

SECRET

and testing of wide-band r-f coaxial (and wave-guide) connectors and fittings. Included are suggestions for future standardization.

411-293 (J. R. Marshall). Describes equipment and methods used in *voltage standing-wave ratio measurements* on connectors, adapters, antennas, etc., in 90- to 10,000-mc range. Details are given on M-115 slotted lines for the 90- to 2,000-mc range, U-1202 measuring lines for the 2,000- to 3,500-mc range, and U-1600 lines for the 3,500-10,000-mc range.

411-TM-118 (M-100, RP-306) (C. M. Daniell). Details procedure in measuring the relative *power supplied to a load through a coaxial transmission line.* The method consists of inserting a probe voltmeter into notches cut in the line at small intervals compared to the wavelength in order to determine the maximum and minimum crest voltages along the line. Then the power in watts is proportional to $E_{max} E_{min}$.

411-255 (A-4300, RP-405) (J. C. Turnbull, J. R. Duggan, R. W. Green). Reviews *measurements on wide-band coaxial lines* preliminary to development of line to transmit 1 kw with minimum standing-wave ratio and attenuation for frequencies in the range from 500 to 2,500 mc. Tests showed that beaded lines are unsatisfactory because of reflections. The best line for low reflection and attenuation appears to be a longitudinally supported line using ½-in. polystyrene tubes to support the inner conductor.

411-137 (R-1000, RP-107) (T. E. Moore, W. G. Wadey). Discusses the use of a variable-length *resonant probe in wave guide* as the reflecting element in a simple tunable stop-band filter for determining the frequency of signals received by AN/APR-5A. The method was found to be unsatisfactory. Determination of the frequency of weak signals will probably be difficult because of an 8- to 10-db off-resonance attenuation. At wavelengths below 4.5 cm the attenuation drops off and at wavelengths greater than 7.5 cm there is too small a rate of change in probe length with resonant wavelength.

411-138 (R-1000, RP-107) (T. E. Moore, W. G. Wadey). Presents preliminary results of measuring the *sensitivity of AN/APR-5A in wave guide,* for each of the possible harmonics over the 3- to 10-cm range. The purpose was to determine the expediency of operating the receiver at frequencies above 6,000 mc. The sensitivity (r-f power necessary to produce an audio signal power equal to the noise power) was found to range from 10^{-10} w at 10 cm to 10^{-7} w at 3 cm, being about the same for each of the oscillator harmonics out to the 9th. More complete and correct data are to be given in 411-152.

411-147 (R-1000, RP-107) (T. E. Moore, W. G. Wadey). Describes experiments in measuring the electrical effect of, and in preventing the condensation of, atmospheric *moisture in wave guides* used for r-f transmission between an antenna and a search receiver. The moisture condensed on 4 sq in. of wave-guide wall, cooled below the dew point, caused a 10 per cent reduction in power transmitted at 11 cm. Condensation can be effectively prevented by circulating the air in the wave guide through a desiccator using magnesium perchloride or silica gel.

411-149 (R-1000, RP-107) (T. E. Moore, W. G. Wadey). Illustrated description of materials and methods to be used in a *wave-guide installation for AN/APR-5A.*

411-79 (R-715, RP-286) (R. H. Hoglund, A. J. Yakutis, J. S. Foster). Describes three *wide-band wave-guide mixers,* one for the 5- to 10-cm range and the other two for the 3- to 6-cm range. The former is a straight, terminated guide with which impedance matching is obtained by nonuniform cross section; it was designed to replace the mixer used in A-2700 receiver, whose characteristics are less uniform. One of the 3- to 6-cm mixers is a reduced scale model of the 5- to 10-cm design, and the other obtains a voltage maximum at the crystal by means of a wave-guide loop.

411-1150 (Q-1900, RP-442) (P. I. Richards). Finds that the optimum *response of nonresonant u-h-f coupling circuits* having a specified form is independent of the type of coupling, whether shunt or series reactance, loops, nonresonant irises, etc. The response is found to depend upon the number of resonant cavities, the bandwidth, the center frequency, and the allowed mid-band loss. Any change in the allowed decibel loss in the pass band has a certain maximum effect that is independent of the number of cavities. The optimum responses for from one to six coupled circuits are shown by curves of insertion loss versus ratio of frequency difference to bandwidth. There are also graphs comparing experimental with theoretical results on two types of wave guide coupled circuits.

411-186 (Q-1900, RP-442) (S. B. Cohn). Presents a method for the *design of broad-band wave guide-to-coax junctions* to be used with wave-guide filters requiring coaxial terminations. The report includes a brief discussion of pertinent transmission line theory, description of various types of junctions, and an account of the test method used. One type of junction (tapered ridge) has a bandwidth

ratio of 2.7 to 1 with a voltage standing-wave ratio of less than 2 to 1.

411-201 (Q-1900, RP-442) (S. B. Cohn, P. I. Richards). Considers the *effect of improper termination on insertion loss* in the filter pass band. Formulas and curves are given for maximum and minimum possible mismatch and insertion loss values in receiver r-f lines in which filters are inserted. An important conclusion is that standing-wave ratios should be kept lower than is ordinarily assumed. The data show that a filter acts properly only when it is terminated at both ends in the impedance for which it is designed.

411-211 (Q-1900, RP-442) (S. B. Cohn). Explains the *properties of ridge wave guide,* a rectangular guide with a rectangular ridge projecting inward from one or both sides. By means of developed equations and curves this type of guide is proved to have a lower cutoff frequency and impedance and a greater higher-mode separation than a plain rectangular guide of the same width and height. Experiments show a high degree of accuracy for the equations. Ridge wave guide has been successfully used as matching or transition elements in guide-to-coax junctions (411-186), as filter and cavity elements, etc. (411-229, and 411-221).

411-221 (A-9000, RP-461a) (H. C. Early). Describes a broad-band *directional pickup and wattmeter for wave guide* or coaxial cable. The pickup consists of a small loop or probe each of whose ends is terminated in a piece of lossy cable. The design with respect to the electric and magnetic fields in the wave guide is such that the power in one piece of cable is proportional to that in the forward wave, whereas the power in the other piece is proportional to the reflected wave. The difference between the two, as read by means of a microammeter and thermocouple connected to the forward piece, is then proportional to the net power into a load or antenna connected to the wave guide or coaxial cable. Such a wattmeter provides satisfactory readings in the range from 8 to 12½ cm.

411-229 (A-9000, RP-461) (H. C. Early). Describes a tapered steelridge wave-guide *dummy antenna* for the 8- to 12-cm range. It can dissipate 1,000-w continuous wave without artificial cooling. The rugged mechanical construction of this dummy load for wave guide makes it suitable for naval use.

411-253 (C-3306, RP-481) (P. A. Pearson). Finds that the *energy loss due to moisture condensation* in wave guide is seldom appreciable unless very large drops and puddles are formed. Measurements of attenuation in 1½- by 3-in. wave guide at 3,000 mc increased from 0.003 db per ft for a light film to 0.005 db per ft for large drops to 1.7 db per ft for large drops and puddles. Sea water caused slightly less loss than distilled water. Measurements also indicated that power loss is approximately linear with standing-wave ratio, becoming 20 per cent for standing-wave ratio of 4.

6.6 NOISE SOURCES AND STUDIES

411-1 (F-700) (J. N. Dyer). *Illustrated description of type 931 photoelectric electron multiplier tube,* which provides theoretical gain as high as 500,000 from low magnitude signal current resulting from minimum light input. Experimental circuit provides 95-μa output with practically uniform response throughout 5-mc bandwidth, and develops 0.38 rms v of noise at grid of first amplifier. Report includes suggested methods for securing necessary 1,200-v operating potential difference from typical power supply.

411-26 (G-100, RP-181) (R. D. Sard). *Calculations of frequency spectrum* of noise from 931 tube, including discussion of factors affecting it. Theoretical results for 70 v per stage show constant output up to 100 mc, after which output drops as frequency increases, being —1 db at 200 mc and —6 db at 500 mc. With 70 v on each of first eight stages and 400 v on last two stages the output drops to only —4 db at 600 mc. These results lead to the conclusion that a net accelerating voltage of 1,500 v graduated from stage to stage would probably permit use of tube as direct-noise source in the 550- to 600-mc range.

411-57 (H-201, RP-187) (J. D. Cobine, C. J. Gallagher). *Report of experiments on operating characteristics* of 931 tube between 50 and 5,000 kc indicates that gain may safely be assumed to be at least 75,000 with 100 v per stage and 0.001 l. In going from 50 to 5,000 kc the noise output drops about —3 db. Because first 15 min of operation causes a decrease of 4 db in noise output, the illumination of the photo-cathode should then be increased to produce relatively constant output. One out of every five or six tubes has to be rejected because of erratic performance. Higher operating voltages can be used to increase the noise output if a pressure chamber be provided to prevent breakdown at high altitudes. The report includes circuit diagrams and graphs of results. It states that the noise is principally due to amplified shot effect in the first stage.

411-TM-119 (H-200, RP-187) (C. J. Gallagher). *Life tests on 931A* phototube show average life of 110 hr.

411-68 (H-200, RP-187) (J. D. Cobine, C. J. Gallagher). *Investigations of the 50- to 5,000-kc spectra* of 11 types of gas tubes indicate RCA-884 as the most promising noise source, followed by RCA-24G, WL 629, and WE 256A. By placing the tube in a strong magnetic field (1,000-1,500 gauss) to suppress objectionable variable-frequency oscillations it produces a relatively high-level spectrum free from peaks and holes. Under normal operating conditions with 30-ma plate current and 550-ohm output resistor, the 884 gives output voltages of 2.8 at 50 kc, 7.5 at 2 mc, and 1.1 at 5 mc, as compared to 0.55, 0.46, and 0.38 v, respectively, as obtained from the type 931 tube with 1-ma plate current and 75,000 gain. The output remains practically constant for long periods of operation. The report contains tables and performance graphs for each type of tube tested. It suggests that maximum output can be obtained by orienting the tube with respect to the magnetic field.

411-TM-1 (H-200, RP-187) (J. D. Cobine). *Early investigation of use of type 884 tube as a noise source.* Conclusions are practically the same as later reported in 411-68.

411-TM-31 (K-400, RP-186) (D. A. Peterson). Summarizes observations of the *performance of the type 884* gas tube (not operated in magnetic field) as a noise source for an a-m radar jammer. The output was found to include oscillations which so masked the noise output as to make the tube much less effective than a type 931. Furthermore the energy distribution is so lacking in uniformity as to make difficult its adaption for use in a broad-band modulated jammer.

411-TM-116 (H-200, RP-187) (J. D. Cobine, C. J. Gallagher, P. S. Jastram). Reports on the *l-f noise spectrum of the 884* gas triode used without a magnetic field for frequencies below about 100 kc. The average spectrum for 15 tubes which were tested shows a practically constant noise output of 66 db from 70 c to 100 kc. The output includes a natural oscillation, usually about 100 kc, which must be filtered out to prevent overloading of amplifier tubes.

411-TM-3 (RRL-H-200, RP-187) (J. D. Cobine). Gives results of tests of the *noise output of the FG178A thyratron* in the frequency range from 0.1 to 9 mc under various conditions. Spectral curves corresponding to optimum conditions show that when the tube is placed in a 1,000-gauss magnetic field the output varies from 80 db above 10μv/kc^{½} at 0.1 mc to 45 db at 5 mc to 30 db at 9 mc, as compared to a practically 4-db (or 3-db) output from a type 931 throughout the same range. (All figures are approximate.) The rms integrated voltage over this range is about 1.6 with a peak of about 6 v. For h-f applications, components below 100 kc should be suppressed because of the possible presence of relatively l-f oscillations. The tube must be oriented relative to the magnetic field in order to provide maximum noise output.

411-TM-38 and **38A** (H-200, RP-187) (J. D. Cobine). Gives results of tests of the *noise output of Sylvania 2C4 and 6D4* miniature gas triodes in the frequency range from 0.1 to 5 mc under various operating conditions. The two tubes have the same noise spectrum and level and are the most efficient of those yet reported in this series of investigations. With a 300-gauss magnetic field and an anode current of 5 ma, the noise output varies from 65 db above 10μv/kc^{½} at 0.1 mc to 76 db at 1 mc, drops to 46 db at 5 mc and to 27 db at 9 mc. The rms integrated voltage over the 0.1- to 5-mc range is 2.1 with a peak of about 6 v.

411-92 (H-200, RP-187) (J. D. Cobine). Describes methods and gives results of testing the *noise output of 6D4* in the range from 25 c to 100 kc. With normal heater current, 5-ma anode current, and 300-gauss transverse magnetic field, the tube produces noise at a level of 10 mv/kc^{½} with little variation from tube to tube. This can be increased to 1 v/kc^{½} by connecting a 0.0005-mfd capacitor from anode to cathode and using a 600-gauss field. These conditions are satisfactory for either spot radar or communications jamming. Random pulses suitable for communications jamming may be produced by the use of a 0.004-mfd capacitor between anode and cathode with proper adjustment of magnetic field and anode current; the resulting noise has a level of about 8 v/kc^{½} between 1 and 6 kc.

411-TM-115 (H-200, RP-187) (J. D. Cobine). Reports on the *l-f noise spectrum of the 6D4.* In a 300-gauss magnetic field the noise output is practically constant at 60 db above 10μv/kc^{½} from 25 c to 100 kc. The rms voltage integrated over this range is 0.1 v with a peak of 6 v due to maximum output at about 1 mc. Placing a 0.0005-mfd capacitor between anode and cathode increases the output by about 20 db and introduces a peak of 18 v due to an oscillation at 200 kc. When this peak is filtered out to prevent overloading of amplifier tubes, the noise should be suitable for both spot and communication jamming. The use of an 0.004-mfd capacitance and simultaneous adjustment of anode current and magnetic field strength raises the noise output to about 110 db in the range from 1 to 10 kc, with a peak noise at about 140 v. This should be an excellent noise source for communication jamming.

SECRET

411-TM-36 (H-200, RP-187) (J. D. Cobine). Gives results of tests of the *noise output of the 2D21* miniature gas tetrode in the 0.1- to 9-mc frequency range under various operating conditions. Spectral curves show that for normal connection in a 1,200-gauss magnetic field the output is practically constant at about 70 db for the frequency range from 0.12 to 1 mc, dropping to 46 db at 5 mc and to 30 db at 9 mc. The noise has a peak of about 5 v. For most effective jamming, the circuit should attenuate frequencies below about 200 kc.

411-TM-121 (H-200, RP-187) (C. J. Gallagher). Investigations of the *noise output of GL-546* indicate too much variation to justify use as noise source.

411-90 (G-105, RP-181) (D. Middleton). Calculation of the *effect of rectification and clipping on the output spectra of 6D4, 884, 178A, and 2D21* noise sources shows that clipping spreads the spectrum and lowers the output level in all cases. The 6D4 yields the greatest spectral spread, closely followed by the 884 and 2D21. A biased quadratic rectifier gives greater output spectral width than does a biased linear detector, if the ratio of cutoff voltage (relative to the operating point) to rms input noise voltage is less than about 2. The report includes a mathematical development of the theory and curves showing spectra for the four types of sources considered.

411-97 (G-106, RP-181) (D. Middleton). Extends the analysis of the *effect of rectifying and clipping the output spectra of the 6D4* (as given in 411-90) to include the effects of overloading the rectifier tube. Overloading is found to clip the "top" of the wave, whereas the cutoff of the tube clips the "bottom" and causes a wider spread in the spectrum. With an overloaded rectifier, whether linear or quadratic, the spread is greatest when the ratio of cutoff voltage (relative to the operating point) to rms input noise voltage lies between ± 1.0 and ± 2.0. The linear is usually to be preferred because of its generally higher output spectral levels. Optimum spread is provided by operation without overloading and by clipping the bottom of the input wave as heavily as possible within the limits of available gain. Severe clipping yields a considerable spectral spread, but at prohibitively low levels. These conclusions are based upon a general mathematical analysis and upon a large number of computed performance curves of the 6D4 tube under various conditions of cutoff, saturation, and rectifier response.

411-74 (H-200 & H-800, RP-187) (J. D. Cobine). Design of 375-gauss *permanent magnets and electromagnets for 6D4* noise source. The permanent magnet consists of two Alnico bar magnets cast in an aluminum frame to give a weight of 9 oz, including the tube, as compared to 6 oz for the electromagnets. The report includes photos, design details, field shapes, and test data.

411-136 (H-200, RP-187) (D. Cobine, C. J. Gallagher, P. S. Jastram). This final report on the *noise characteristics of Type 884 and 2050* gas tubes concludes that neither is as good as the 6D4 used with magnetic field. The conclusion is based upon measurements of output voltage uniformity, magnitude of noise output, freedom from undesirable oscillation, and low power requirements. The noise spectrum of the 884 without magnetic field is fairly uniform from 25 c to 100 kc with a strong oscillation at 100 kc which must be filtered out. Considerable data are given on the tube-to-tube variations found with the 884. The output of the 2050, using the control grid as the anode, is relatively flat from 25 c to 30 kc with a strong oscillation at about 50 kc.

411-TM-69 (H-200, RP-187) (P. S. Jastram). One-sided *clipping of 6D4 noise* output has two effects. First, the general level is reduced. Second, the low-frequency components (1-3 mc) are reduced more than the high-frequency components (3-9 mc), making a flatter spectrum. For unclipped noise the level at 5 mc is 30 db below the 1-mc level, whereas with extreme clipping the 5-mc level is only 11 db below the level at 1 mc.

411-76 (H-800, RP-187) (J. D. Cobine). Describes two l-f *noise generators using the 6D4* noise source. One (H-804) develops 180-v peak-to-peak noise voltage across a load of 4 kilohms. The other (H-805) develops 5-v peak-to-peak noise voltage across a load of 100 ohms. Both have a substantially flat noise spectrum from 500 c to 100 kc. In each the 6D4 is followed by a low-pass T filter to suppress frequencies higher than 100 kc. The decibel output is considerably increased by a capacitive shunt across the output of the 6D4 tube. With the high load impedance generator the noise is quite evenly clipped on both sides of the voltage wave. With the low-impedance generator the noise is quite strongly clipped on the negative side. The report includes photo, circuit diagram, and noise spectrum for each generator.

411-169 (H-200, H-800, RP-187) (J. D. Cobine, J. R. Curry). Summarizes results of investigating *behavior of 6D4 as noise source* for the 0.5-mc to 5-mc range. Based upon a large number of reported measurements, the recommended operating conditions are (1) the tube should be used with a 375-gauss permanent magnet oriented with field trans-

verse to discharge path, (2) anode current 5 ma, (3) load resistance 20,000 ohms or higher. The spectrum maximum is then at 700 kc, the level is about 79 db above $10mv/\sqrt{kc}$, the peak-to-peak output is 18 v, and the rms voltage is 2.5 v.

411-124 (H-205, RP-187) (P. S. Jastram). Describes a *peak-reading voltmeter* that may be used to measure random noise. The instrument has 1- to 150-v amplitude range and a frequency coverage from 50 c to 30 mc. The circuit, its operation and calibration, are described in detail, as are also the design principles.

411-162 (H-200, RP-187) (J. D. Cobine, J. R. Curry). Describes a *range extender for a sound analyzer* (General Radio Type 760A) whose upper limit is extended to 200 kc in order to facilitate noise measurements at higher frequencies. This is accomplished by means of an oscillator and tuned mixer to beat the noise at high frequencies down to a fixed frequency band on the 760A. The setting of the variable-frequency oscillator gives the frequency of the noise components being measured.

411-225 (H-800, RP-187a) (J. R. Curry). Summarizes experience in *equalizing noise amplifiers* to provide a high noise level with approximately flat spectrum in the 0.1- to 5-mc range from a 6D4 (or 931) source. Results are embodied in five schematic diagrams to be used by inexperienced builders of 6D4 noise amplifiers for outputs of approximately 60, 85, 95, and 100 db in the 0.1- to 5-mc range and 120 db in the 0.5- to 2.5-mc range. (Zero 6 = $10\mu v/\sqrt{RC}$.) Equalization is accomplished by manual adjustment of compensating circuits to give optimum indication on a spectrum analyzer to which a noise voltage is applied. A simple shunt or series peaking circuit is used for compensation at high frequencies and a parellel RC circuit in series with the load resistance for low frequencies. The report includes a brief, clear discussion of noise spectra, instantaneous, rms, and peak-to-peak voltages, clipping, and power, as well as their measurement and specification. Experimental results show the effect of clipping on the noise spectra, the unclipping effect of filters, and the amplifier response to noise and sine waves.

411-232 (H-200, and G-107, RP-187 and 181) (J. D. Cobine, C. J. Gallagher, R. Weinstock, F. Bloch). Gives results of experimental and theoretical investigations of the production of *noise from hot-cathode gas tubes* with and without an external magnetic field. Experiments on the effect of arc discharge in gases were made with spectrum analyzers and wide-band "scopes." The discharges generate oscillations superimposed on random noise in a band having a width of several megacycles. There are both plasma-ion oscillations and oscillations of ions in the cathode potential minimum. The oscillations may be suppressed by a transverse magnetic field when the anode is so shielded that no electrons can reach it from the cathode. The magnetic field also increases the level of the h-f components of the noise by focusing the ionizing electrons into a narrow region near a tube electrode. The noise level also depends upon the pressure, being highest at about 20 μ. The report includes a description of an experimentally developed tube giving a wider noise band than that from 6D4.

411-239 (H-200, RP-187) (S. Ruthberg). Finds that *cold-cathode gas-tube noise generators* are less practical than the hot-cathode type because of the higher voltages and currents required. The discharges from the two kinds of tubes are similar in appearance and behavior. Types tested were the glow tube, mercury arc with mercury-pool electrodes, and a corona-discharge monocle. Of these, the glow tube is best for noise production controlled with a transverse magnetic field. The level and slope of its spectra compare favorably with those of 6D4, especially in the region up to 1 mc.

411-258 (H-200, RP-187) (P. S. Jastram, C. J. Gallagher). Discusses the theory and operation of the *6D4 spectrum checker*, an instrument which indicates the spectral distribution of the noise from an available gas triode in the range from 100 kc to 5 mc. The device comprises a two-stage amplifier, filters, diode rectifier, and meter. The results of a sample set of measurements are tabulated.

411-260 (H-200, RP-187) (P. S. Jastram). Exhaustively summaries and discusses the elementary *theory of noise.*

778-8 (NDRC-C63) (M. E. Campbell). Gives the circuit and characteristics for a *voice-frequency noise* generator employing a 2051 gas tube as the noise source.

(January 30, 1943)

931-5 (RP-243) (L. R. Koller). Discusses the *constriction oscillator as a noise source.* This mercury-vapor discharge tube, wherein the arc passes through a constriction between the anode and cathode, gives a nonuniform spectrum with an output dependent upon the pressure of the mercury vapor. The tube life of 5-10 hr is limited by the sputtering of the cathode. The high rate of cleanup prevents the use of permanent gases instead of mercury.

(November 20, 1943)

966-4 (NDRC 15004) (H. H. Benning). De-

SECRET

scribes preliminary models of three types of *a-f noise generators* originally intended as modulation sources for communication transmitters which are converted to jammers. They are convenient for laboratory or training use. One consists of a motor-driven shaft in a cup of carbon granules. Another is a motor-vibrated carbon transmitter button. The third type uses a 2050 gas tube to drive a 6AG7 amplifier.

(May 26, 1943)

1060-1 (462, RP-196) (A. M. Glover, R. W. Engstrom, W. J. Pietenpol). Describes a *grid-controlled photomultiplier* (C-7102) and its application to regenerative amplification of noise output in the 0-5 mc/sec range. With a tube similar to the 931-A, feedback from the ninth dynode to the grid is found to increase output noise by 10 db over 2-mc band-widths at any frequency up to 5 mc.

(May 16, 1944)

1060-2 (462, RP-196) (A. M. Glover, R. W. Engstrom, W. J. Pietenpol). The final RCA report on the investigation and manufacture of *noise sources*. These include the 931-A, the C-7102, and the 884 with various gases. The 931-A is found to have better life than the 931; improvements possible from minor design changes are unimportant; complete redesign is impracticable. Facts relative to C-7102 are given in 1060-1. Helium gas in 884 is best adapted to noise production; at optimum pressure of 700-750 μ only one-tenth as strong a magnetic field is required to suppress oscillations as in the case of argon.

(March 7, 1945)

1176-1 (RP-311) (S. Ballantine). Gives the results of tests of *Tungar bulbs as noise generators*. They show no special merit as compared with other gas tubes requiring less cathode power.

(February 11, 1944)

1176-2 (RP-311) (S. Ballantine, E. Osterland). Discusses the use of *transformer coupling with gas-tube noise sources* instead of the conventional resistance coupling. Circuits are given for type 884 and 2050 tubes used for spot jamming of communications from a 28-v d-c supply. No magnetic field is used. The behavior of the 2050 is found to be better than that of the 884. Output is not sufficient to provide 100 per cent modulation of transmitters.

(January 6, 1944)

1176-3 (RP-311) (E. Osterland). Reports the results of *noise source investigations* at Ballantine laboratories. Studies were made of gas tubes, electrolytic interrupters, and spark gaps as noise sources for jamming communications.

(August 1, 1944)

6.7 MISCELLANEOUS RESEARCH AND DEVELOPMENT

411-9 (A-700, RP-147) (R. B. Barnes). Describes three untuned receivers for detecting radar signals over wide ranges of carrier frequencies and repetition rates. Each consists of an antenna, *r-f band-pass filter*, crystal or diode detector, and audio amplifier. The filter is designed to make the receiver sensitive only to a selected r-f range. In the filter structure sections of coaxial transmission line are used in place of lumped inductances. Simple design formulas for the capacitances are given in terms of the upper and lower cutoff frequencies, section length, and desired characteristic impedance, with specifications and performance curves (theoretical and actual) for the 170- to 270-mc range.

411-28 (A-700, RP-147) (S. B. Cohn). Contains *design equations and performance curves for six u-h-f filters*. The types include (1) low-pass for 100-ohm load with cutoff at 150 mc, (2) high-pass for 100-ohm load with cutoff at 150 mc, (3) combined (1) and (2) in series, (4) band pass for 150-300 mc for 42.5-ohm load, (5) band pass for 300-460 mc for 50-ohm load, and (6) band pass for 100-200 mc for 50-ohm load. Loaded short-section of coaxial transmission line are used as high-Q inductances for all cases. The capacitances are metal disks connected to the center conductor and closely spaced from the outer conductor by means of dielectric material. The report includes data on termination with either crystal or diode detector and practical information on construction.

411-TM-102 (M-125, RP-306) (J. G. C. Swinney). Briefly discusses the design, construction, and performance of a *75-mc low-pass filter* using lumped constants. The filter is of standard design with M-derived end sections and a T center section working into a 50-ohm line. The discussion includes a graph of measured attenuation versus frequency and an estimate of 60 db attenuation at 75 mc.

411-113 (M-4601, M-4602, RP-286) (P. L. Harbury). Design of one- and two-section high-pass filters with cutoff at 900 mc when working between 50-ohm terminations. Report includes application of design equations from 411-28 and sketches, attenuation characteristics, and standing-wave characteristics of the two filters.

411-115 (Q-1600, RP-286) (P. I. Richards). Gives equations for designing *resonant-section coaxial filters*. The derivation of the equations is based upon a general method for analyzing all types of coaxial filters in terms of matrix notation, as explained in some detail. Experimental measurements

are given on four structures, including a tunable (13-7.5 cm) double-T band pass and a similar I section, an m-derived band pass, and a three-section band pass, all having relatively sharp cutoff.

411-115A (Q-1900, RP-442) (P. I. Richards). Gives equations for designing an easily constructed *high-pass coaxial filter* consisting of several sections of coaxial line separated by capacitances. The equations were derived by the method given in 411-115. Constructional details and performance curve are given for a 1,700-mc high-pass filter.

411-115D (Q-1900, RP-442) (P. I. Richards). Supplements 411-115 by presenting improved design equations and curves for seven types of *resonant-section coaxial filters.*

411-163 (Q-1900, RP-442) (S. B. Cohn). Presents design equations and curves for an easily constructed *microwave low-pass filter* which may be built either in coaxial line or wave guide. Treatment includes elimination of spurious response and consideration of insertion loss. The method is exemplified by computing the dimensions for a 50-ohm termination coaxial filter having a pass band up to 3,450 mc, an attenuation of greater than 30 db above 4,050 mc, and no spurious responses below 10,000 mc or near 24,000 mc. Discontinuity capacitances at changes in cross section are taken into account in the development of the design equations.

411-115B (Q-1900, RP-442) (P. I. Richards). Derives design formulas for *minimizing spurious responses* in a low-pass filter that is designed in accordance with equations from 411-163. The formulas involve cancellation of some of the spurious pass bands in order to provide characteristics approaching those of an ideal low-pass filter.

411-161 (W. G. Wadey). Complete illustrated description and explanation of operating technique, including harmonic frequency chart for more accurate determination of frequency of high-pass filter with variable cutoff, 3,000-10,000 mc (RP-107, R-1024). This filter consists of a wave-guide section with a movable wall which can be adjusted from a fully open position for cutoff at 3030 mc to a fully closed position for cutoff at an infinite frequency. The filter is built into 1 x 23/32-in. wave guide and is fitted with a calibrated dial reading directly in thousands of mc. It may be readily adapted for remote reading and control through a flexible shaft. Designed for u-h-f operation of APR-5A, it is also useful in eliminating interference when searching for only higher-frequency signals. Another suggested use is as a "line stretcher" in wave guide.

411-234 (Q-1900, RP-442) (S. B. Cohn, P. I. Richards). Is primarily concerned with the *mechanical design of u-h-f filters* developed by the Q-1900 project. Emphasis is placed on the necessity for terminations in the characteristic impedance for which a filter is designed, and test procedures are given for insuring such terminations. A brief discussion of discontinuity and other second-order effects is followed by suggestions for practical layout and construction of filter structures.

411-240 (Q-1900, RP-442) (K. R. Spangenburg). Gives the insertion loss versus frequency *characteristics of band-pass filters* composed of one, two, or three lossless resonant circuits in a loosely coupled cascade connection between a source and a load impedance. The effects of coupling upon bandwidth and insertion loss variations are also discussed. The method of analysis depends upon finding the complex roots of the determinants of the mesh equations. The bandwidth of a three-circuit filter is found to be approximately 40 per cent greater than that of a two-circuit filter with the same coupling.

411-281 (R. R. Rhigher, F. M. Gager). Describes two methods for *measuring insertion loss of microwave filters.* The accuracy of one method depends upon the calibration of the attenuator of a signal generator. That of the other method depends upon the square-law operation of a crystal detector. Either method gives the attenuation in terms of the characteristic impedance insertion loss of the filter under test.

411-21 (D-400, RP-178) (J. P. Woods). Contains complete data for design and construction of 400- to 2,600-c *transformers and chokes* used in radio power supplies. Full information in the form of tables, graphs, and practical comments is given for designing power units ranging from 9 to 900 volt-amperes as provided by nine sizes of RRL-standard-shape laminations with progressive factor of approximately 2.

411-37 (D-400, RP-178) (J. P. Woods). Illustrates and describes a three-element L-C *network for regulating a-c voltage* from a small variable-speed motor-generator driven by storage battery. The network maintains constant voltage output for reasonable variations in battery voltage, provided that the motor does not vary more than ± 10 per cent from its nominal speed, the generator has an approximately linear voltage-frequency characteristic, and the load has approximately unity power factor.

411-78 (D-400, RP-178) (J. P. Woods). Develops general principles, equations, and graphs to be applied in the *design of small transformers* working in the frequency range from 100 to 3,000 mc.

After proving that the power loss is minimized when the copper and iron losses are approximately equal, equations are developed to relate power loss and transformer weight to output volt-amperes, frequency, dissipation per unit surface area, iron and copper constants, and relative transformer dimensions. From these equations are determined the relative dimensions for minimum transformer weight and per cent power loss. These establish an optimum shape for laminations, which is the basis for graphs showing the relations between output volt-amperes on the one hand and circular mils per ampere, flux density, and lamination width on the other. A final graph relates design frequency to output volt-amperes per pound of transformer. These data are used in 411-21.

411-264 (G-611) (D. Middleton). Develops an approximate theory for *eddy-current loss in transformer cores* excited by video random noise and high-frequency (mc) sine waves. Formulas and graphs showing the variation of skin depth and mean eddy-current loss with frequency and thickness of lamination are derived from a solution of the field equations governing the distribution of electric and magnetic fields in thin rectangular laminae. Skin depth is found to decrease with increase in frequency, thickness of lamination, and effective permeability and conductivity of the core. In voltage-fed transformers the mean loss is approximately inversely proportional to the square root of the bandwidth. In current-fed transformers, it is directly proportional. Consideration of the advantages and limitations of the theory and its approximations and suggestions for reducing eddy-current losses are included in the report.

411-244 (H-900, RP-187) (J. D. Cobine, J. R. Curry, C. J. Gallagher, S. Ruthberg). Outlines a procedure for designing *video transformers for noise voltages*. The procedure is based on exciting impedance and power loss (hysteresis and eddy) data for Hipersil, Monimax, and B9W4A. As a result of techniques for measuring these properties, which techniques are fully described, it is concluded that Monimax has the lowest losses with noise excitation. The data, both calculated and empirical, are shown by numerous curves. The procedure is applied to the design of two transformers operating in a Class B noise amplifier to deliver 350 w with a 2.5-mc bandwidth.

411-67 (C. W. Oliphant) (Beaver I). Presents results of 10-day *search watch at Bird Cape*, Amchitka, near Kiska, in 180- to 225-mc frequency range. The search equipment comprised two S-27 and one SX-28 receivers with CUO high-frequency converters and horizontal half-wave dipole antennas. All observed radar signals were believed to come from friendly sources. The report concludes with recommendations for future similar missions.

411-TM-103 (A-3700, RP-321) (W. G. Dow). Gives tentative specifications for a *30-kw air-borne*, 9- to 12-kv, d-c *power source* to be installed in the bomb bay of a four-motored bomber. The equipment includes a 160-hp air-cooled auxiliary engine, flexible coupling and gear box, 40-kw, 400-c generator, transformer, and rectifier tube rack.

411-89 (R-2000, RP-306) (S. B. Cohn). Describes a system for *measuring the frequency response and sensitivity of receivers* operating in the range of frequencies from 50 to 1,000 mc. The equipment consists essentially of a large, constant field strength, conducting ground plane (galvanized iron mesh) in which may be inserted a calibrated transmitting antenna (variable-length cylindrical stub adjusted to resonance) and a receiving antenna (type designed for ground plane mounting). The field strength of the receiving antenna is shown to be equal to

$$\frac{7.44\,E}{d}\sqrt{\frac{G}{R}}\ \text{volts/meter},$$

where E is the voltage between the ground plane and the base of the transmitting antenna, d is the distance in meters between the antennas, R is the resonant resistance of the transmitting antenna ($X = 0$), and G = gain of transmitting antenna compared to $\lambda/2$ dipole ($G = 2$ for $\lambda/4$ and 1.39 for $3\,\lambda/4$). When all factors except E are held constant during a given frequency-response run, the field strength is directly proportional to E, as measured by an r-f voltmeter built into the base of the antenna. The usual procedure is to maintain E constant and read the receiver output. But if the receiver does not obey a definite detection relation, its output can be held constant by varying E. Auxiliary equipment includes the r-f voltmeter (bolometer), 70-db audio amplifier, a-f voltmeter, r-f signal generators with low-pass filters, and r-f voltage regulator. The details for this equipment and the operating technique are described in the report.

411-TM-105 (R-2000, RP-306) (S. B. Cohn). Describes an *r-f voltage regulator* specifically designed for use with the equipment mentioned in 411-89 and having many other possible uses listed in the document, which shows photos, block and circuit diagrams. The device automatically maintains a constant r-f voltage level at any arbitrary circuit point.

411-TM-99 (G-700, RP-299) (Donald Foster)

Concludes that the *jamming of German altimeters* in various tactical situations is impracticable not only because of the great power required but also because of doubt as to the value of doing it.

411-TM-47 (D-419, RP-178) (J. P. Woods). Contains 16 plotted curves of 60-c *sparkover tests across gaps in air at low pressures.* Data cover sphere gaps, needle gaps, and glass bushings for various gap lengths and pressures. They indicate a general straight-line relationship between sparkover voltage and pressure. An additional curve shows the relationship between pressure in inches of mercury and altitudes up to 50,000 ft.

411-TM-98 (R-1700, RP-117) (R. C. Raymond, S. B. Cohn). Describes a *wide-band regenerative circuit* which permits the reradiation and amplification of a signal on the frequency at which it is received. The radiating time is long compared to the silent period during which the signal is received. Lack of available personnel has prevented the final development and possible applications of the circuit.

411-107 (Z-3600) (L. E. Rayburn, H. Kees). Preliminary experiments with broad-band *signal-repeating systems,* consisting of an APR-4 receiver, ARQ-8 transmitter, and an auxiliary mixer, indicate that each particular application requires a "tailor-made" installation. This requirement is due mainly to the large number of spurious responses in the receiver output to be retransmitted. The system will evidently work on almost any desired receiving and transmitting frequencies if the equipment be carefully installed with reference to location of receiver, transmitter, and antennas.

411-111 (Z-1500, RP-242) (R. L. Hammett). Comprehensive illustrated description of *Raven installations on Albatross I* (Navy PB4Y-2 reconnaissance aircraft). Special emphasis is placed on the ten antennas variously used for search, jamming, and DF, showing patterns, standing-wave ratios, and test results as well as discussing their installation and use. Information is also given about the installation of AN/APA-17, AN/APA-24, AN/APR-1, AN/APT-1, AN/APQ-2, and wave guide for AN/APR-6. A number of installation features designed to reduce operator fatigue and to increase the utility of this type of aircraft when searching for enemy radars are also discussed.

411-165 (S. W. Athey). Briefly describes ten *available RRL films* for instruction or demonstration. Subjects covered by the confidential lists are the M-2600 direction finder, A-500 Tuba, Albatross I, Carpet spot jamming, E-510 high-pass filter, and Window against HPG radar. Those covered by the secret list are tests of Window against SCR-584, Window on SCR-648 radar, effects of jamming on SCR-521 radar, and E-2400 f-m complex target indicator.

411-171 (R-900, RP-286) (P. I. Richards). Derives *probability formulas* that two events, each recurring at a definite period and lasting for a definite time interval, will occur simultaneously at least once during some specified time interval. The results are applicable to such problems as finding the probability that within 5 min an aircraft can make radio contact with an air traffic control tower where a receiver is being tuned back and forth over a frequency band (the aircraft may be assumed to transmit a 5-sec call every 20 sec). From the formula it is also possible to find what should be done in order to improve the probability of contact. In general, the results are applicable to any problem that reduces to a question of the overlap of rectangular waves.

411-177 (J. G. C. Swinney). Gives design information on three types of *probe voltmeters,* their calibration and use in measurement of frequency, velocity of propagation or relative power in concentric transmission line, adjustment of antenna systems and oscillators, and determination of the characteristic impedance of a transmission line.

411-217 (G-2000, RP-349) (F. Bloch). Discusses the theory and design of *low-radar-reflectivity cable* used in towing targets for antiaircraft practice. The sample cable consists of a core of stranded steel wires covered with a thin insulation of polyethylene over which is wound a protecting steel armor for the "open sections," with a thin metal foil between the insulation and the armor for the "shorted sections." The "open sections," because of forced circulation of electric current in the armor around the cable, have a higher inductance than the "shorted sections" with which they are alternated. The operating principle is that of a transmission line with periodically varying self-induction. The effective cross section of the fabricated cable is about one-fifth that of a continuous steel cable of the same dimensions, as confirmed by laboratory tests. Field tests have yet to prove whether this low reflectivity is sufficient for practical protection.

411-272 (G. E. Hulstede). Considers the *effect of signal intercept probabilities on design of search receivers* and DF antennas. The probability information is obtained from a mechanical computer which simulates a radar signal and a receiving antenna, both sweeping in azimuth, and a search receiver sweeping in frequency, the sweep rates being adjustable, as is also either the antenna beamwidth or receiver acceptance band. The recorded data are

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plotted as curves to show various effects for given parameters. Curves indicate, for example, that less time is required to intercept a signal if the receiver has a high sweep rate, that intercept occurs more quickly as the acceptance bandwidth is increased, or that a rotating type of DF antenna causes a longer time between intercepts than does an omnidirectional antenna. Such typical findings assist in solving design problems.

411-276 (S. W. Athey and C. Gray). Considers *methods for photographing cathode-ray tube screens,* with special reference to the problems encountered in RCM studies and investigations.

411-285 (W-100) (R. K. Vermillion). Describes a *high-speed linear sweep circuit* suited for oscillographic study of transient waveforms. The circuit includes means for producing a sawtooth pulse from either a positive or negative pulse, a means for adjusting the time delay between the initial triggering pulse and the start of the sweep voltage, and a means for calibrating and adjusting the linearity of the sweep voltage. Circuit is designed for use with any conventional oscillograph having direct horizontal deflection plates and intensity grid terminals.

RCM APPLICATIONS

7.1 AIRBORNE RCM SYSTEMS

966-51 (RP-440) (H. H. Benning, G. J. Heinzelman). Describes *communication Ferret C-1,* a B-24 plane equipped to search for and monitor enemy transmissions in the 0.55- to 200-mc range. Positions are provided for three operators each of whom handles an automatic search receiver and APA-23 recorder, a manually operated monitoring receiver and voice recorder of transmissions observed thereon, and a second voice recorder of dictated data. Two modified R-45/ARR-7 receivers are used for the 0.55- to 28-mc range, R-44/ARR-5 for the 28- to 80-mc range, and R-54/ARR-4 for the 80- to 300-mc range.

(June 8, 1945)

966-52 (RP-440B) (E. O. Bernard, C. R. Eckberg). Describes *modifications of R-24/ARR-5* for Ferret use in searching and monitoring the 28- to 82-mc band. The changes permit satisfactory performance, as discussed in detail, when two receivers are operated from a single antenna or from the same power supply.

(August 23, 1945)

966-53 (RP-440) (R. V. Crawford). Describes *modifications and performance of R-45/ARR-7* receivers to permit operation of two on a single antenna and from a single power supply for Ferret use.

(August 22, 1945)

1045-TM1 (BAD 100—BD 102, RP-986) (J. W. Keuffel). Describes *modifications to Jackel* AN/ART-3 to correct defects that would prevent immediate operational use of experimental models. The report includes recommendations for future designs based on test experience.

(September 7, 1944)

1045-TM2 (RP-986) (D. K. Reynolds). Describes the procedure and gives the results of jamming trials of Jackal AN/ART-3. The general conclusions are that German tank radio communication is effectively jammed when airborne Jackel sets are staggered in frequency and that SCR-508, -608, -509, and -609 are not severely affected. Ground trials indicated that this jammer when mounted on a truck or when installed on a hillside could be usefully employed to cover confined areas.

(August 21, 1944)

1045-MR3 (D. K. Reynolds). Describes the *installation of Jackel* AN/ART-3 in B-24 aircraft of the 8th Air Force.

(August 17, 1944)

1045-TM3 (RP-986) (R. C. King). Describes the procedure and gives the results of *field tests of Jostle IV* in jamming German and American 30- to 34-mc equipment. The results indicated more effective jamming of German tank radio communications (amplitude-modulated) than of SCR-609 (frequency-modulated). Harmonic radiation from the jammer is negligible and the fundamental spectrum is uniformly satisfactory.

(February 23, 1945)

966-13 (RP-236) (C. L. Cahill). Gives results of *v-h-f jamming at Orlando.* Jamming was successful whenever the jammer was closer to the receiver than was the signal transmitter.

(September 22, 1943)

7.2 OPERATIONAL CONSIDERATIONS AND TESTS

966-17 (RP-326) (R. L. Robbins). Reports on slight *RCM activities in Tennessee maneuvers* during July 1943. Four ground-based jammers with 20- to 100-w output and improvised vocal or mechanical noise were available. Most of the conclusions are of a tactical nature.

(September 24, 1943)

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966-23 (RP-326) (R. L. Robbins). Reports *radio activities in Tennessee maneuvers* in autumn of 1943. All operations were of too short duration for RCM to prove itself in a spectacular manner.

(December 28, 1943)

1045-2 (RP-987) (S. Hansen). Describes the procedure and gives the results of *field tests of Peter* in jamming a British 590-mc coastal radar from a British ship. Tests with an unmodified jammer and a jammer with a five-stage repeater amplifier (voltage gain of 800) indicate that the amplification causes a small craft to appear as a cruiser to the radar operator.

(January 10, 1943)

1045-4 (RP-987) (S. Hansen, H. H. Race). Gives results of *field tests of Peter* comprising an u-h-f amplifier having a voltage gain of 2,000 and a bandwidth of 14 mc centered at 560 mc. Using bare dipole antennas without reflectors and inclined 45 degrees from horizontal (receiving 25 ft and retransmitting 40 ft above water) the set gives an intensified echo equivalent to a destroyer at all ranges down to 5 miles. The tests indicate that the signal may be made to simulate a light cruiser either by adding reflectors or by increasing the mean antenna height to 45 ft.

(February 4, 1944)

1045-9 (J. T. Wilner, et al). Estimates the monthly *RCM requirements of the 8th and 9th Air Forces* as a minimum of 1,000 radar jammers, great quantities of communications jammers, and extensive facilities for investigating the characteristics of enemy radars.

(June 20, 1944)

1045-11 (RP-987). Recounts such *American British Laboratory* [*ABL*] *activities for RCM phases of Neptune* operation (the invasion of Normandy) as may be of use in future operations. The chief work, aside from training operators and participating in basic planning and in field tests, was in correcting certain undesirable characteristics of the RCM equipments, particularly as regards interference to other allied services. Much work was also done in installing and adjusting jammers on various vessels of the U. S. Navy. The report is terminated with brief mention of specific difficulties encountered with CXFR, TDY, British Carpet II, APR-1 with panoramic adapter, APR-6, and RDL-Blinker.

(November 22, 1944)

1045-MR2 (RP-984) (J. D. Noe). Describes the prototype installation and tests of *AN/APA-17 in a B-17* aircraft. It is found that the accuracy of a bearing can be approximately judged by an experienced operator on the basis of the pattern displayed on the cathode-ray tube. Accuracy on a sweeping signal is less than on a locked signal and tends to be less on a lobe-switched than on a non-lobe-switched signal. Accuracy on a non-lobe-switched, locked signal appearing approximately fore or aft of the aircraft should be within ± 3 degrees. The report also describes the organization of 94th Bombardment Group for operational use of the equipment.

(August 13, 1944)

1045-MR5 (RP-984) (J. D. Noe). Presents and analyzes *data obtained by AN/APA-17* on 13 operational missions in the European Theater. The equipment is found to be suitable for determining locations of enemy radar, mapping radar-controlled flak areas, predicting flak in time for neutralizing or evasive action and for investigating the operational procedure of enemy radars. High-caliber operators, well-trained, are essential.

(October 27, 1944)

1045-TM5 (L. B. Lusted). Gives data on *AJ devices* in a *Small Wurzburg* which had been captured and assigned to ABL for repair and modification. The Window AJ devices included means for utilizing the doppler effect to distinguish between fast moving aircraft and slow moving Window, a differentiating circuit to distinguish visually between a fixed target echo and the random character of the Window return, and a circuit for making the same distinction aurally. The AJ devices against jammers included means for quickly and easily shifting from a jammed to an unjammed frequency, DF means for measuring the bearing and elevation of a jammer, and means for measuring range by selecting the most favorable polarization in order to minimize the jamming.

(March 21, 1945)

1045-TM4 (J. G. Stephenson). Describes *modifications to Rug and Carpet I and III for spot jamming.*

(February 27, 1945)

1045-TM6 (RP-303) (G. H. Klemm). Describes a *modification Kit for AS-69/APT* (M-2202) antenna for operation in the 450- to 500-mc band.

(April 19, 1945)

1045-TM7 (RP-987) (M. B. Adams). Describes procedure and gives results obtained in measuring d-c *power available for RCM in B-17 and B-24* aircraft. The data indicate that operation of APT-4 transmitter does not constitute an excessive drain on the power system of either type of aircraft.

(May 7, 1945)

SECRET

1045-MR4 (L. B. Lusted). Describes the *installation of 17- to 84-mc receiving and recording equipment* in four P-38 "Droopsnoot" aircraft used for special investigations.

(September 28, 1944)

1045-MR8 (J. W. Keuffel). Describes the *installation of Jackal* (new XA-2 model) in B-24 aircraft of 36th Squadron. Two were put in each aircraft, one on each side, in order to reduce the number of abortions due to equipment failure.

(May 24, 1945)

1045-MR12 (J. M. Hollywood, P. M. Keeler). Discusses the theory and practice of designing a *barrage-jamming screen against German EW radar.* Computations indicate the watts per megacycle that should be delivered to the antennas and charts show this quantity as a function of screening depth for a given distance of screen from the enemy radars. Examples are given for figuring the necessary aircraft installations and dispositions. For instance it is found that an 80-mile front can be screened by 6 B-24's each equipped with 25 APT-1 transmitters. Practical details are given for such an installation using one antenna for each two transmitters.

(May 30, 1945)

1045-MR14 (C. B. Clark). Summarizes the work done in making and testing a *Ferret installation in a B-24J* aircraft for the 8th Air Force to use in checking a jamming screen. The installation includes antennas and antenna switches, racks and cables for two receivers, and two APA-11 pulse analyzers, remote indicator for magnesyn compass and the required inverters, starting switches, relays, and control boxes.

(May 28, 1945)

1045-MR15 (RP-987) (R. S. O'Brien). A comprehensive compilation of postwar information on the *effectiveness of RCM against German flak radar.* Extensive interrogations and inspections indicate that RCM, particularly simultaneous Window and Carpet jamming, reduced the effectiveness of flak to one-fourth the value obtained with no jamming under blind conditions. RCM compelled optical fire direction to be used even under adverse conditions. Fully half the German h-f research personnel were working on AJ devices involving a frenzied patching of old equipment. World War II was over before any appreciable number of 9-cm GL and AI equipments could be placed in service. The German radar status at the end of the war was about the same as that in the Allied laboratories about 1942.

(June 16, 1945)

411-44 (X-100) (F. E. Terman, W. D. White). Discussion of various factors affecting the *distance from a radar system for which a jammer-equipped bomber is self-screened* leads to the formula (when ground effects are neglected)

$$R = 1.76\ (10^{-4}) \sqrt{\frac{P_t G_t A_e}{B P_j G_j} C}\ ,$$

where

R = minimum distance (in miles) for effective jamming,
P_t = effective peak power of radar transmitter,
G_t = power gain of radar transmitter antenna relative to isotropic radiator, free-space conditions, in the direction of the target,
A_e = echoing area of airplane or target in square meters,
C = camouflage factor for type A or plan-position indicator presentation (includes pulse length and repetition rate),
B = receiver bandwidth (in megacycles) ahead of 2nd detector,
P_j = jamming noise power per megacycle of bandwidth,
G_j = power gain of jamming antenna relative to isotropic radiator in direction of radar.

Besides considering and evaluating each of these factors, the report presents graphs and tables of the calculated effectiveness of Mandrel, Dina, Carpet, Rug, Carpet Sweeper, and High-Power Carpet with respect to Freya, Hoardings, Wurzburg, and Japanese systems. There is also a short discussion on the screening of a group of aircraft.

411-48 (X-402) (H. A. Chinn). A chart of tentative data on the *characteristics of enemy radar* equipment.

411-93 (G-700, RP-186) (T. S. Kuhn, P. Sutro). Formulates a theory for approximate calculation of the power density of *radar echoes from naval targets* and the computation of jamming powers and minimum jamming distances within the radar horizon. Values for minimum jamming distances are obtained graphically in connection with formulas. For low-power jammers the antennas should be placed as high as possible, whereas lower heights provide maximum effectiveness for high-power jammers.

411-TM-106 (G-700, RP-299) (T. S. Kuhn). Preliminary report on expected *size of echoes from naval targets,* operational effectiveness of available jammers, and power requirements for proposed jammers.

411-157 (G-704, RP-209) (M. Hamermesh). Applies data on 100-mc measurements of *radar cross*

SECRET

sections of aircraft models to determination of cross-sectional areas giving maximum range for early warning and susceptibility to GL. The measured data are averaged over a cone of small solid angles to allow for the small aspect variations of a plane in flight. Effective area is found to depend not only on the type of aircraft and its aspect, but also upon the radar frequency and polarization. Values are tabulated for B-24 and B-17E aircraft, singly and in formation, at various azimuths with vertical and horizontal polarizations. The discussion also covers anticipated results from future measurements on 500 mc and their application to the Wurzburg radar, the general conclusion being that there will be a decrease in the dependence of cross section on polarization.

411-157A (G-704, RP-299) (A. T. Goble, M. Hamermesh, E. Presly). Presents data on measurements of *radar cross sections of aircraft models.* The data are plotted as a function of aspect for B-29 at 75 and 225 mc, TBM at 200 mc, B-17 and B-24 at 450 mc, and A-20 at 600 mc. The graphs are to be used in solving operational problems on the design of jamming antennas, analysis of flak risk, evaluating the screening effectiveness of Window at various concentrations, etc., as illustrated by a few typical examples.

411-251 (G-2700, RP-299) (D. A. Park, R. D. Sard). Surveys the problem of predicting the *effectiveness of jammers against GL and SLC radars.* It is concluded that allowances should be made for variation of airplane cross section with aspect and for deviation of practical jamming signals from pure unclipped noise. The computation procedure is (1) to plot a jamming map (based on experimentally determined characteristics of a specific type of radar and jammer, particularly the antenna) and (2) to determine the operational effectiveness of the given pattern by translating it into a map showing regions where guns can shoot most accurately or where searchlights are most dangerous. The chance of a hit under given tactical conditions is then found graphically and compared with the chance of a hit in the absence of jamming so as to give a numerical measure of effectiveness. This figure gives a good measure of the relative merits of different jamming transmitters and antennas against different radars.

411-224 (G-1800, RP-406C) (R. Weinstock). Discusses the use of airborne corner reflectors for *misdirection of lobed GL radar* to protect bombers from flak. From graphs of calculated sizes of reflectors necessary to modulate the target echo at the enemy's lobe-switching rate it is concluded that the reflectors would have to be too large for practical use against 75-mc and 200-mc radars. The report concludes that reasonably small corner reflectors would be useful against microwave radar systems.

411-228 (S-1800X, RP-474) (M. Hamermesh, R. Weinstock). Calculates *RCM to nullify blind bombing effectiveness* of British H_2S Mark II in the 3,280- to 3,440-mc band and of AN/APQ-13 and AN/APS-15 radars in the 9,375 $\pm$ 40-mc band. The estimates indicate that screening 1 sq mile of "city" from H_2S requires at least 180 corner reflectors with 3-m edges, from AN/ equipment at least 450 corner reflectors with 2-m edges, and from either type of equipment a prohibitive amount of Chaff. The use of ground-based c-w jammers is found to be more feasible, requiring a beam power (product of power by antenna gain) per megacycle of about 5 w against H_2S, 24 w against APQ-13, and 55 w against APS-15. An area of about 12 sq miles can be screened against a single H_2S by 16 jammers and against a single APQ-13 or APS-15 by 32 jammers. Brief consideration of covering an area of several square miles with the radiation from a pulsed jammer suggests the possibility of effective screening when the peak power of the transmitter is equal to that of the enemy radar.

411-129 (G-2400, RP-258) (L. R. Koller). Concludes from experimental observations that *radar echoes from naval spoofs* (seaborne corner reflectors) cannot be distinguished, by A-scope observation on any single radar system, from echoes due to warships. In both cases the fluctuations of the echoes are random in amplitude and in frequency. From observations with a 700-mc and a 3,000-mc radar system, for which the difference in response is approximately 12 db, it is concluded that the use of two systems of widely different frequency should provide a feasible means for distinguishing spoofs from ships. Further tests are to be made with frequency modulation of a pulsed radar system as a discriminating method. Further experiments on airborne corners are necessary before an adequate conclusion can be reached.

411-188 (E-2400, RP-406J) (E. R. Brill, R. H. Hoglund). Considers methods for *discrimination between radar echoes from naval vessels and decoys.* The methods are based upon a theoretical analysis of the difference in reflection from a point source (for a decoy) and from a multipoint source (for a vessel). The analysis predicts that the scope indication of the echo pulse due to a vessel will (1) be the more greatly distorted in shape and (2) show a greater variation in amplitude for small change in transmitter frequency. Experimental veri-

fication of (1) was obtained by modifying a search radar to provide a 3- to 6-mc i-f bandwidth, a 1.5- to 3-mc video bandwidth, and a delayed A scope expanded to between 100 and 200 yd per inch. Verification of (2) was obtained by means of a mechanical f-m attachment to produce a 2-mc transmitter frequency deviation at a low audio rate. Neither of these modifications impair normal performance. The first is simpler and preferable for immediate application to present types of search radars to be used in identifying decoys.

411-95 (Z-3000) (R. D. Sard). Summarizes facts known about *German radar systems from the RCM viewpoint.* Equipments and methods used for air defense and offense, naval radar, and IFF are described and discussed with respect to their vulnerability to countermeasures. The air defense systems include (1) search sets giving range and bearing: Freya, Chimney, and Hoarding; (2) tracking sets giving elevation, bearing, and range: Small and Giant Wurzburgs for planes and for ships, (3) aircraft-interception Lichenstein (Fuge-202). The air offense systems include the bomber tail warning sets Fuge-214 and Fuge-216 and the aircraft-to-surface-vessel sets Fuge-200 and Fuge-213. Naval radar is considered under (1) land-based surface watching sets, (2) U-boat sets FuMO-30, FuMO61, and Fuge-200U, (3) ship-borne radar. The IFF sets described are the Fuge-25a and Fuge-25. The more important systems are illustrated by sketches. The survey indicates absence of microwave equipment and lack of equipment for navigation and blind bombing.

411-99 (G-1800, RP-406) (R. Weinstock). Suggests a method for *shielding surfaced submarines from radar detection.* Based on the results of mathematical analysis, the report finds that approximately bell-shaped wire mesh screens will shield the conning tower and other objects on deck and that a downwardly curved screen will shield the above-water portion of the hull from ship-based or airborne radars. The screens should be so arranged as to provide no specular echo and to minimize the nonspecular (diffracted) return by having the upper and lower edges of the screens horizontal or extending into the sea surface. Numerical comparison of echo values from noncamouflaged and from shielded submarines shows that shielding causes an appreciable reduction in the maximum range of radar detection.

411-133 (Z-5000, RP-169) (W. D. White). Summarizes the results of a study of *power requirements for shipboard 10-cm jammers.* Calculations based upon an analysis of experimental data are presented in the form of curves showing the optimum jammer antenna height and the beam power (transmitter power less transmission line loss times antenna gain) required to screen the broadside aspect of a destroyer, light cruiser, and battleship. Another curve shows the percentage increase in beam power necessary with nonoptimum antenna heights. The general conclusion is that present available jamming equipment and techniques are adequate, provided that the countermeasures operator has satisfactory means for quickly setting his transmitter on frequency.

411-141 (L-1400, RP-406) (D. R. Scheuch). Describes a *modified ASC-1 for operation with dual polarization.* The simultaneous presentation by L scope directly compares the relative amplitudes of vertically and horizontally polarized received signals, thus providing a specific means for testing the response of microwave confusion reflectors to both polarizations. Modifications comprise replacement of the original antenna system by the rotating antenna and parabolic reflector unit of an APG-1 automatic GL set and the addition of a video switching unit and power supply, an L scope and power supplies, a junction box and an antenna sector-scan permitting PPI search operation up to 180 degrees in azimuth. The equipment is installed in a light truck with trailer for operation in transit. The report gives a detailed illustrated description of the modified system with schematic diagrams of the added equipment.

411-140 (G-509, RP-103) (F. Bloch, M. Hamermesh). Analyzes the *effectiveness of countermeasures* by means of the mathematical theory of probability. Equations are given for obtaining a quantitative estimate and procedures are described for judging the significance of the result. The general method of solving a problem is to compare the observed results with what might be expected if the countermeasure were completely ineffective.

411-122 (L-1003, RP-XX) (F. P. Cowan). Outlines *requirements for spot-frequency jamming* in the 100- to 1,000-mc range and in the 10-cm region, as found from experience in AJ field tests. The treatment covers transmitters, antennas, and receivers for search, setting on, and monitoring, with recommended installation and operating procedures. Emphasis is placed on the advantages of corner reflector transmitting antennas and on the use of APA-6 pulse analyzer with APR-4 receiver for setting on and monitoring. Recommendations include adequate shielding of the receiver and both antennas in order to isolate the receiver from the transmitter. The report includes descriptions of two

ship-borne 100- to 1,000-mc installations meeting these requirements and of a 10-cm jamming installation using beacon antennas and a spectrum analyzer.

411-226 (S-1300, RP-459) (J. J. Wittkopf). Gives the results of *airborne jamming tests against AI radars*. The tests were intended to aid in the development of tactics to facilitate the escape of a pursued aircraft. The report concludes that evasive action without jamming is not dependable. Escape is probable when continuous jamming is powerful enough to so overload the radar receiver that it is impossible to DF on the jamming signal. Because Window is so easily recognized, its use alone is not dependable, whereas it has good possibilities when used with jamming.

411-245 (E/L-2800, RP-411) (R. H. Hoglund, F. P. Cowan). Outlines plans for field tests of the *vulnerability of AN/APS-4* radar to jamming with E-3200 test transmitter (see 411-256 in Section 5.2) operating in the X band. This project was scheduled for transfer to the Navy when RRL terminated. Tests were also to be made of various AJ modifications of the APS-4 receiver, including an FTC coupling circuit and a grid-bias type of gain control. A special camera mechanism for photographing the scope images is described.

411-250 (E/F6010, RP-338) (R. L. Henkel, T. S. Kuhn, L. B. Lusted, R. E. Reid). Describes a method for the measurement of *jamming effectiveness* and applies the method to a comparison of jamming transmitters and to the solution of operational screening problems. The method requires experimental operation of a flexible synthetic radar to supply data for plotted curves showing the effectiveness of a jammer operating into a receiver. The curves delineate minimum observable steady pulse as a function of receiver frequency. (See 411-251.) Quantitative results for 200 mc are given for APT-4, APT-1, APQ-2, and a test transmitter when they were operating into APR-1, APR-4, and RDO. The tests indicated the marked superiority of APT-4 with respect to the magnitude of the signal and the frequency band over which it will screen. The results differ greatly from and are more reliable than those predicted by the "accepted power" theory of jamming.

411-278 (W-200, RP-299) (J. F. Youngblood, B. M. Kuck). Points out the faults in various experimental methods for finding the *formation factor* or ratio of effective echoing area of n planes to that of a single plane when observed at the same aspect. This factor is used in estimating the number of planes in a formation and in calculating the jammer power necessary to shield a specified formation. The report concludes that a fairly satisfactory practical method is to obtain the average amplitude of a number of pulses and to record the instant when a predetermined level is reached. A proposed instrument for doing this is described in 411-257.

411-257 (W-200, RP-299) (R. K. Vermillion). Describes the P-102 instrument to be used with the SCR-545 or other radar in *measuring the formation factor* of aircraft. The instrument is essentially a constant-speed tape recorder which is marked by two sets of positive pulses. One set consists merely of time-reference pulses of either 0.1- or 1-μsec intervals. The other set is produced by adding a series of from 5 to 50 video signals from the radar receiver (slightly modified) to provide high enough voltage to trip a trigger circuit, and thus produce a series of pulses. These are interpreted as explained in 411-278.

GLOSSARY

AA. Antiaircraft.

ABL-15. American British Laboratory of NDRC Division 15.

A-C. Alternating-current (adj.).

ADRDE. Air Defense Research and Development Establishment (Br. Army). (Later changed to RRDE—Radio Research and Development Establishment.)

A-F. Audio-frequency (adj.).

AFC. Automatic frequency control.

AI. Aircraft interception (airborne radar for plane-to-plane detection).

AIL. Airborne Instruments Laboratory.

AJ. Antijamming.

ALSOS. A scientific mission sent to Germany immediately after World War II under the auspices of OSS with the purpose of gathering information on scientific subjects in enemy countries, particularly from scientific sources.

AM. Amplitude modulation (noun).

A-M. Amplitude-modulated (adj.).

AN. Army-Navy.

ANGEL. An electromagnetic-wave reflector (usually a metallic corner reflector) used to create radar echoes for deception and confusion purposes.

ASB. A Navy airborne vs. surface target radar.

ASCOPE. A radar indicator on which signals corresponding to targets appear as vertical deflections on a horizontal-range trace.

A.S.E. Admiralty Signal Establishment (Br. Navy).

ASV. Air-to-surface vessel—airborne radar for detecting seaborne targets.

AUTOMAT. An automatic jamming system.

AVC. Automatic-volume-control.

BAGFUL. A British receiver for use in examining in detail any particular band. Has a tape recorder that lasts for 8 hours. Covers frequency band of 300-400 Mc; 380-500 Mc; and 480-610 Mc.

BAGPIPES. A type of communication jamming modulation which sounds like the playing of bagpipes.

BARRAGE JAMMING. The simultaneous jamming of a number of adjacent channels or frequencies.

BEAGLE. An automatic search jammer.

BEAVER. Ground-based radar search DF and jamming mission of which there were 4. All involved the 1st Signal Service Platoon (Special).

BEECHNUT. A ground-to-aircraft communications system employing two-tone keying.

BENITO. German aircraft navigation system operating in the 40-Mc band. Provides indications of azimuth and range.

BIG BEN. Code name given to the German V2 rocket.

BIRDNESTING. Formation of tangled clusters of chaff during Window operations, resulting in poor dispersal and consequent low reflection efficiency.

BLANKET. A system of direction-finding deception.

BOOZER. An airborne warning receiver that intercepts and distinguishes between German ground-controlled interception, GL, and AI transmissions.

BROADLOOM (CXFR). 500-mc jamming transmitters using tunable magnetrons.

BROOM. An automatic search jammer.

BSCOPE. A type of radar indicator, presenting range versus azimuth angle, in rectangular coordinates.

BTL. Bell Telephone Laboratories.

CAAC. Countermeasures Air Analysis Center, AAFPOA.

CARPET. Airborne, noise-modulated, barrage-jamming transmitter.

CATALINA. Navy PBY Flying Patrol Boat.

CBS. Columbia Broadcasting System.

CH. Chain-Home, code word for system of low frequency radars installed by British in 1938 along their own coast.

CHAFF. Electromagnetic-wave reflectors in the form of narrow metallic strips approximately one-half wave length long used for creating radar echoes for confusion purposes.

CHI. Generic designation for type of Jap radar.

CHICK. An expendable jammer.

CIC. Combat Information Center.

CIGAR. A large ground-based communications jammer.

CINCPAC. Commander-in-chief Pacific.

CONFUSER. A mechanical noise generator.

CORNER REFLECTOR. An electromagnetic-wave reflector consisting of three intersecting, mutually perpendicular, plane metallic surfaces.

CURTAIN. Airborne VHF homing equipment designed for use against German VHF.

CV. Aircraft carrier.

CVL. Light Aircraft carrier.

C-W. Continuous-wave (adj.).

D-C. Direct-current (adj.).

DF. Direction finding (noun).

DINA. Direct-noise amplifier. This is a code name given to a series of transmitters supplying random-noise output without a carrier frequency.

DINAMATE. A DINA transmitter plus a receiver (MATE). When the latter is tuned to a signal to be jammed, the former is automatically tuned to the same frequency.

ELECTRA. German 200-500 Mc multi-lobe Lorenz system (a bomber navigational aid).

ELEPHANT. A very complete shipborne jamming system.

ELMER. A communications deception device designed to permit a single station to emit signals simulating an Army net.

EW. Early warning.

FARNS. Farnsworth Telephone and Radio Corporation.

FD. The Mark IV Navy fire-control radar.

FEAF. Far East Air Forces.

FERRET. An aircraft carrying a large amount of radio-countermeasures investigational equipment.

FISHLINE. Same as TINSEL ROPE.

FLUTE. A type of magnetron.

FM. Frequency modulation (noun).

F-M. Frequency-modulated (adj.).

FREYA. 120-Mc German early-warning ground radar equipment; modified to cover 75-100 Mc and 120-180 Mc.

FT&R. Federal Telephone & Radio Corporation.

FUGE FUGE. (Followed by type No.) German radio or radar (Funkgerat or Funk messergerat).

GASTON. An audio noise generator.
GCI. Ground-controlled interception—the direction, from the ground, of friendly fighters with the objective of intercepting enemy planes. Instructions are based on data obtained by radar.
GE. General Electric Company.
GEORGE BOX. An early-warning radar antijamming attachment.
GL. Gun-laying-radar used to direct gunfire.
GM. Guided missiles.
GOLDAMMER. Same as STENDAL B.
GR. General Radio Company.
GSI. Geophysical Services, Inc.
GULLS. Confusion reflector.
H-DIENST. German listening service for plotting Allied aircraft by their radio transmissions.
H2S. British high-altitude-bombing radar device—10 cm (early form), 3 cm (later form). Scope gives presentation of land flown over.
H2X. An American type of radar high-altitude-bombing device—3 cm.
HOARDINGS. German early-warning radar, also called Mammut, in frequency range 123 to 128 Mc.
I-F. Intermediate-frequency (adj.).
IFF. Identification Friend or Foe. System of radio interrogation and reply (if friendly) generally used in connection with radar for identifying aircraft.
IT&T. International Telephone & Telegraph Co.
JACKAL. An airborne, frequency-modulated, barrage-jammer for communications channels.
JAGDSCHLOSS. 150-Mc GCI with continuously rotating array and PPI. A ground radar equipment.
JAN. Joint Army-Navy.
J&B. Jansky & Bailey.
JNW. Joint New Weapons Committee of Joint Chiefs of Staff.
JOSTLE. British, airborne, barrage jammer for use against German tank and paratroop communications.
J/S. Jam-to-signal (ratio).
K BAND. 11,000 to 33,000 Mc.
KITES. Airborne, self-opening, and free-falling corner reflectors (same as ANGELS).
KNICKEBEINE. (Headache) German 30-33 Mc long-range Lorenz beam system for blind bombing, using intersecting beams to mark the target. (A bomber navigational aid.)
LAB. Low-altitude-bombing attachment for SCR-717-B and AN/APQ-13 equipped planes.
L BAND. 390 to 1,550 Mc.
LC. Inductance capacitance.
LISTENING-THROUGH. Observation of a signal being jammed through the jamming.
LORAN. Long-range radio-navigation system.
LORENZ. German firm. It built a 600-Mc radar designed for GL but relegated to coast watching (ground radar equipment).
MANDREL. Airborne, noise-modulated, barrage-jamming transmitter primarily for the 85- to 135 Mc region. (e.g., AN/APT-3).
MEACONING. The destruction of the accuracy of a radio-navigated system by deceptive transmissions designed to imitate actual radio-navigational aid signals.
MOONSHINE. A pulse-repeating system designed to conceal the magnitude and extent of a radar target.
NDRC. National Defense Research Committee.
NEPTUNE. Code word for Naval Port of Normandy Invasion. (Also Neptun Gerat—German AI and tail-warning radar in frequency range 150 to 182 Mc.)
NRL. Naval Research Laboratory.
OCSIGO. Office of the Chief Signal Officer.
OSRD. Office of Scientific Research and Development.
OSURF. Ohio State University Research Foundation.
OTC. Officer in Tactical Command.
PAD. A noncoherent-pulse jammer.
PANTHER. A panoramic receiver.
PERFECTOS. Airborne radar equipment designed to trigger the German IFF, thus measuring range to and permitting homing on German fighter formations.
PETER. A pulse-repeating system for confusing angular definition of radar sets.
PETER PAN. A signal-repeating jamming system.
PETTICOAT. Mission to install RCM equipment in British Naval vessels for use in Normandy invasion.
PF. Proximity fuze.
PIANO. A signal-repeating jammer.
PICCOLO. A type of magnetron.
PICKETS. Small vessels usually disposed to give advance warning of enemy activity.
PIMPERNEL. An automatic receiver and drive unit for setting jamming transmitters to frequency.
PING PONG. Accurate British DF system used to determine coastal radar locations.
PORCUPINES. B-29 with barrage-jamming installation for 70 to 200 Mc. The numerous stub antennas gave plane appearance of a porcupine.
PPI. Plan-position indicator. Indicator for radar providing polar-coordinate presentation of azimuth and range.
PRC. Panoramic Radio Corporation.
PRF. Pulse-repetition frequency.
QUADO. A jamming frequency alignment indicator.
RC. Resistance capacitance.
RCA. Radio Corporation of America.
RCM. Radio countermeasures.
R-F. Radio-frequency (adj.).
RHB. Radar homing bomb.
RI. Radio intercept.
RL. Radiation Laboratory at the Massachusetts Institute of Technology.
ROPE. Electromagnetic-wave reflectors, for the creation of artificial radar echoes, in the form of a long (about 400 ft) metallic ribbon.
RRL. Radio Research Laboratory.
RT. Radio Telephone (British Term).
RUFFIAN. German navigational system operating on 66.5-70 Mc using three stations. Gives bomber the ground speed when 15 kilometers from his target and sounds a horn at the bomb release point on the target. It is a grid of "coarse" and "fine" beams over the target area.
RUG. An airborne low-powered radar jammer for use in the frequency range 180-450 Mc.
SAMBO. The detection of propeller modulation and attempt to use it as identification, particularly by coating one or more propeller blades with nonreflecting material.

S BAND. 1,550 to 5,200 Mc.
SE. S band radar for installation on surface craft for the detection of surface craft.
SEETAKT. 350-380-Mc Freya-type coast watcher. Also called Calais Anlage. A ground radar equipment.
SETTING-ON. Alignment of the frequency of a jamming transmitter with the frequency of a signal to be jammed.
SHORAN. A "line of sight" precision bombing system (in the 300-Mc band) which employs two ground stations and an airborne transmitter and receiver with computer.
SLC. Searchlight control (radar used for aiming searchlights).
SPOT JAMMING. The jamming of a specific channel or frequency.
STENDAL B. A German antijamming device.
STOPWATCH. An automatic jammer alignment system.
TAIL. Attachment to permit homing on jammer or radar signals.
TBF. Type of torpedo bomber (Grumman).
TBM. Type of torpedo bomber (Martin).
TEA. A shipborne jamming transmitter for use against guided missiles.
TINSEL. Conversion of existing transmitters to jammers by providing source of noise for modulation purposes (British term).
TINSEL ROPE. Tuned rope made from tinsel.
TRE. Telecommunications Research Establishment (UK).
TUBA. A 50-kw ground-based jammer used against German AI radar.
TURNSTILES. Confusion reflectors made from three half-wave dipoles of wire held mutually perpendicular at the centers.
U-H-F. Ultrahigh-frequency.
VB. Dive bomber.
V-E. Victory in Europe.
V-H-F. Very-high-frequency.
V-J. Victory in Japan.
VOFLAG. A two-tone six-element error-proof code system for a teleprinter communication.
VT. Torpedo bombers.
WE. Western Electric Company.
WEST. Westinghouse Electric & Manufacturing Company.
WHIP. Antenna.
WINDOW. The use of CHAFF, ANGELS, or other reflectors for radar confusion purposes.
WURZBURG. German radar tracking sets used for ground-controlled interception, searchlight control, and gun-laying in frequency range 520 to 590 Mc.
WURZLAUS. German AJ device. Coherent pulse system for discriminating between slowly moving Window echoes and aircraft echoes.
X BAND. 5,200 to 11,000 Mc.

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A few laboratories issued technical memoranda, in addition to technical reports. These were numbered in accordance with the same system except that the letters "TM" preceded the serial number. Thus the fourteenth technical memorandum issued by the laboratory operating under Contract OEMsr-411 would be numbered 411-TM-14.

Abstracts of the Division 15 Technical Reports listed in the following bibliography are given in the Appendix. Since report titles are sometimes not altogether descriptive, reference to these abstracts is recommended.

Numbers such as Div. 15-402.4-M1 indicate that the document listed has been microfilmed and that its title appears in the microfilm index printed in a separate volume. For access to the index volume and to the microfilm, consult the Army or Navy agency listed on the reverse of the half-title page.

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SECTION

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854. *Peter Tests for British Navy*, Siegfried Hansen, Report 1045-2, Project RP-156, Harvard University, ABL, Dec. 18, 1943. Div. 15-403.1-M3

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857. *Progress Report of the American British Laboratory Period Ending March 25, 1944*, J. W. Dyer, Report 1045-5, Harvard University, ABL, Mar. 25, 1944. Div. 15-124-M1

858. *Report on Sleeve Antenna BC-900*, R. F. Lewis and G. H. Klemm, Report 1045-6, Harvard University, ABL, Apr. 17, 1944. Div. 15-331.14-M1

859. *Report on Sleeve Antenna BC-500*, R. F. Lewis and G. H. Klemm, Report 1045-7, Harvard University, ABL, Apr. 17, 1944. Div. 15-331.14-M2

860. *Modification of BC-639A Receiver to Reduce Pulse Interference*, G. P. McCouch, Report 1045-8, Harvard University, ABL, May 17, 1944. Div. 15-212.11-M5

861. *A Study of the RCM Requirements of the 8th and 9th Air Forces*, W. E. Evans, Report 1045-9, Harvard University, ABL, June 20, 1944. Div. 15-322.124-M5

862. *Modification of British Ground Cigar for Spot Jamming*, W. E. Evans, Report 1045-10, OSRD Liaison Office WA-3057-2, Harvard University, ABL, July 20, 1944. Div. 15-402.2-M4

863. *Report of ABL Activities in Planning and Installations for RCM Phase of Operation Neptune (Invasion of Normandy)*, F. C. Cahill, Report 1045-11, Project RP-987, OSRD Liaison Office WA-3304-1, Harvard University, ABL, Nov. 22, 1944. Div. 15-124-M2

864. *Broad-Band DF System*, J. V. Granger, Report 1045-12, Project RP-982, OSRD Liaison Office WA-4390-11a, Harvard University, ABL, Apr. 23, 1945. Div. 15-313.2-M2

865. *Modifications to Jackal AN/ART-3 (XA-1)*, J. W. Keuffel, 1045-TM-1, OSRD Liaison Office WA-3045-3. Harvard University, ABL, Sept. 7, 1944. Div. 15-401.2-M3

866. *Jamming Trials of Jackal AN/ART-3 (XA-1)*, D. K. Reynolds, 1045-TM-2, Harvard University, ABL, Sept. 21, 1944. Div. 15-401.2-M4

867. *Jostle IV Field Tests*, Richard C. King, 1045-TM-3, Project RP-986, OSRD Liaison Office WA-3969-10A, Harvard University, ABL, Feb. 23, 1945. Div. 15-401.21-M1

868. *Modifications to Carpet I (AN/APT-2), Carpet III (AN/APQ-9), and Rug (AN/APQ-2) Transmitters for*

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Spot-Frequency Jamming, J. Gregg Stephenson, 1045-TM-4, Project RP-997, OSRD Liaison Office WA-4143-1, Harvard University, ABL, Feb. 27, 1945. Div. 15-322.124-M8

869. *Installation of Anti-Jamming Devices in the German Ground Radar Equipment FuSE 62*, Lee B. Lusted, 1045-TM-5, Project RP-998, OSRD Liaison Office WA-4236-2, Harvard University, ABL, Mar. 21, 1945. Div. 15-711.2-M1

870. *Modification Kit for AS-69/APT (M-2202) Antenna for Operation 450-500 Mc Band*, G. H. Klemm, 1045-TM-6, Project RP-303, OSRD Liaison Office WA-4363-1, Harvard University, ABL, Apr. 19, 1945. Div. 15-332.11-M4

871. *Availability of D-C Power for RCM in B-17 and B-24 Aircraft*, Milton B. Adams, 1045-TM-7, Project RP-987, OSRD Liaison Office WA-4446-13B, Harvard University, ABL, May 7, 1945. Div. 15-322.15-M4

OSRD APPOINTEES

DIVISION 15

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C. G. SUITS

Officers

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H. M. JOHNSON, *Special Assistant to the Chief*

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C. B. JOLLIFFE
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F. E. TERMAN

Consultants

H. H. BEVERAGE
R. BOWN
H. A. CHINN
A. B. CLARK
A. W. HULL
R. W. LARSON
FRANK LEWIS

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-63	General Radio Company 30 State Street Cambridge, Massachusetts	Development of the SCR-587 (ARC-1) search receiver.
OEMsr-89	Farnsworth Television & Radio Corporation Fort Wayne, Indiana	Radio interference generator.
NDCrc-100	Ohio State University Research Foundation Columbus 10, Ohio	Antenna patterns for aircraft.
OEMsr-285	International Telephone & Radio Manufacturing Corporation 67 Broad Street New York, New York	Radio interference generator.
OEMsr-411	Radio Research Laboratory, Harvard University Cambridge, Massachusetts	Operation of a central laboratory for RCM research and development.
OEMsr-626	Bell Telephone Laboratories (through Western Electric Company) 463 West Street New York 14, New York	Study of interference generation.
OEMsr-653	Columbia Broadcasting System 485 Madison Avenue New York 22, New York	The development of a listening through radar countermeasures system and construction of model thereof.
OEMsr-747	Westinghouse Electric Corporation, Research Laboratories East Pittsburgh, Pennsylvania	Design, development, fabrication, and testing of resnatron tubes.
OEMsr-759	Ohio State University Research Foundation Columbus 10, Ohio	Radiation characteristics of airborne antennas.
OEMsr-778	Bell Telephone Laboratories (through Western Electric Company) 463 West Street New York 14, New York	Study of radio jamming.
OEMsr-806	Galvin Manufacturing Corporation 4545 Augusta Blvd. Chicago, Illinois	A contract for the transition and procurement of a limited number of units of the RRL-C1100 (AN/APR-2) search receiver.
OEMsr-807	Delco Radio Division, General Motors Corporation Kokomo, Indiana	Emergency transition contract intended to assist in the procurement of Division 15 developments. No activity occurred under this contract.
OEMsr-808	Galvin Manufacturing Corporation 4545 Augusta Blvd. Chicago, Illinois	Emergency transition contract intended to assist in the procurement of Division 15 developments. No activity occurred under this contract.
OEMsr-867	Columbia Broadcasting System 485 Madison Avenue New York 22, New York	Research, development and the construction of special radio apparatus in the field of radio countermeasures.
OEMsr-895	RCA Victor Division of Radio Corporation of America 66 Broad Street New York, New York	Radio countermeasures research and development.
OEMsr-923	General Radio Company 30 State Street Cambridge, Massachusetts	The development of special test oscillators and signal generators.
OEMsr-931	General Electric Company, Research Laboratory Schenectady, New York	Research on radio and radar countermeasures.
OEMsr-936	Federal Telephone & Radio Corporation 67 Broad Street New York, New York	Study of jamming and anti-jamming of radio telegraphy.
OEMsr-937	Federal Telephone & Radio Corporation 67 Broad Street New York. New York	A radio communication system protected against interference.

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-940	Bell Telephone Laboratories (through Western Electric Company) 463 West Street New York, New York	Radio barrage jamming and anti-jamming studies.
OEMsr-966	Bell Telephone Laboratories (through Western Electric Company) 463 West Street New York, New York	Study of radio jamming and anti-jamming.
OEMsr-993	Bell Telephone Laboratories (through Western Electric Company) 180 Varick Street New York 14, New York	Scanning reception in radio countermeasures.
OEMsr-1005	General Radio Company 30 State Street Cambridge, Massachusetts	Development of special signal generators for receiver vulnerability tests at the Jansky and Bailey laboratory.
OEMsr-1019	General Electric Company, Research Laboratory Schenectady, New York	Studies and experimental investigations in connection with development and testing of a line of tunable magnetrons to cover frequency of 500 to 30,000 Mc.
OEMsr-1024	Jansky and Bailey 1222 Wisconsin Avenue Washington 7, D. C.	Susceptibility tests on communications receivers.
OEMsr-1034	Federal Telephone & Radio Corporation 67 Broad Street New York, New York	New L-band transmitter tubes.
OEMsr-1043	RCA Victor Division of Radio Corporation of America Lancaster, Pennsylvania	Model shop facilities and research and development of CW magnetron tubes.
OEMsr-1045	Radio Research Laboratory, Harvard University Cambridge, Massachusetts	The operation of an RCM laboratory in Great Britain.
OEMsr-1060	RCA Victor Division of Radio Corporation of America Lancaster, Pennsylvania	Investigation and development of electronic noise sources.
OEMsr-1107	Westinghouse Electric Corporation, Research Laboratories East Pittsburgh, Pennsylvania	High power ground communications jammer.
OEMsr-1138	Panoramic Radio Corporation 245 West 55th Street New York, New York	Electronic tuning for panoramic reception.
OEMsr-1176	Ballantine Laboratories 1 Fanny Road Boonton, New York	Research on fundamental processes for production and development of noise by various sources.
OEMsr-1179	Midwest Radio Corporation 909 Broadway Cincinnati, Ohio	Prototype model production (Pad).
OEMsr-1222	Bell Telephone Laboratories (through Western Electric Company) 463 West Street New York 14, New York	Vacuum tube research and development.
OEMsr-1232	Delta Star Electric Company 2437 Fulton Street Chicago 12, Illinois	Engineering and development of two models of the RRL A-500C (Tuba) equipment for the British under lend-lease requisition.
OEMsr-1275	Federal Telephone & Radio Corporation 67 Broad Street New York, New York	500 Watt amplifiers for AN/ARQ-10.

CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTS (*Continued*)

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1302	Ring & Clark Munsey Building Washington, D. C.	Consulting services on radio countermeasures.
OEMsr-1305	Airborne Instruments Laboratories (under the auspices of Columbia University) 160 Old Country Road Mineola, New York	Research and development on radio, radar, guided missiles countermeasures, and counter-counter measures.
OEMsr-1309	Westinghouse Electric Corporation 5901 Breakwater Avenue Cleveland, Ohio	Development and production of 6-20 kw transportable communications jammers—30-50 Mc—frequency modulated over 4 Mc band at 240 cps.
OEMsr-1310	Westinghouse Electric Corporation 5901 Breakwater Avenue Cleveland, Ohio	Production of 10-20 kw transportable communications jammers—30-50 Mc—frequency modulated over 4 Mc band at 240 c.
OEMsr-1324	International Diesel Electric Company, Inc. 36-50 38th Street Long Island City, New York	Power supply units for 20 kw communication ground jammers (Cigar).
OEMsr-1328	Maryland Engineering Company Pikesville, Maryland	Development and production of 18 rhombic antenna assemblies for use with AN/MRT-1.
OEMsr-1357	Litton Engineering Company P. O. Box 749 Redwood City, California	Development and supply of electron tube models.
OEMsr-1428	Erco Radio Laboratories 231 Main Street Hempstead, New York	CW spot jammer (Stopwatch).
OEMsr-1430	Federal Telephone & Radio Corporation 67 Broad Street New York 4, New York	Development and supply of electron tube models.
OEMsr-1456	Sylvania Electric Products 60 Boston Street Salem, Massachusetts	Development and supply of electron tube models.
OEMsr-1458	Federal Telephone & Radio Corporation 67 Broad Street New York 4, New York	Direction finders and D-F countermeasures.

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Office of the Executive Secretary, OSRD, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department. They were assigned Division 15 RP numbers as indicated. Reference to pages 511–518 will provide information as to the Division 15 contractor to whom each project was assigned.

Service Project Number	*Subject*	*RP No.*
	ARMY AIR FORCES PROJECT NUMBERS	
AC-69	Chaff cutters	RP-103a
AC-71	Development of Chaff (Window) dispenser	RP-406b
	Ext. of: Jettison type Chaff dispenser for fighter aircraft	RP-406b
	Ext. of: Consultant service (AAF) on development and improvement of Chaff dispensers	RP-273
AC-290	Radar search and analysis	RP-408a, b, c
AC-290.12	Research and development of airborne single dial search receivers with image response and spurious responses from all sources reduced to a minimum and operating from 1,000 to 12,000 Mc	RP-286a, c RP-435a, b, c RP-442b RP-472
AC-290.13	Research and development of airborne single dial search receivers with image response and spurious responses from all sources reduced to a minimum and operating from 11,000 to 33,000 Mc	RP-286
AC-290.14	Research and development of necessary antenna systems for equipment developed under Project AC-290	RP-107c RP-138d, f
AC-290.15	Research and development of the necessary adapters, analyzers, recorders, and other auxiliary equipment for use with receivers developed under AC-290 and the assembly of various receivers and auxiliary devices into smoothly working systems	RP-425a, b RP-447
AC-290.16	Investigation and development of improvements for existing airborne search receivers and making recommendations thereon to the air technical service command	RP-286c RP-442b RP-443 RP-448
AC-290.17	Study of the radar RCM search problem above 1,000 Mc with a view toward recommending improvements in existing radar Ferret aircraft installations and planning for future Ferrets	RP-315
AC-290.18	Research and development of necessary search receiving systems for use in determining the extent of the enemy's employment of radio types of proximity fuses	RP-117a, d
AC-291	Communications intercept and analysis	
AC-291.01	Study of the communication, navigation and special radio RCM search problems with a view toward recommending improvements in existing communication Ferret aircraft installations and planning for future Ferrets	RP-298d RP-440a, b
AC-292	Radar AJ and AJ training	
AC-292.01	General study of means of reducing the effect of all types of enemy offensive countermeasures	RP-214 RP-318 RP-406a
AC-292.03	Study of vulnerability of selected airborne radar sets and making recommendations for operating procedure to combat jamming or reflection devices and for changes that can be made to improve performance	RP-367 RP-368 RP-452
AC-293	Communications AJ and AJ training	
AC-293.01	Study of vulnerability of selected airborne radio sets and making recommendations for changes that can be made to improve performance in the presence of intentional interference	RP-189 RP-192 RP-463 RP-464 RP-465 RP-466 RP-467
AC-293.04	Research and development of protected airborne communications systems	RP-124
AC-293.05	Studies of J and AJ of radio telegraphy	RP-109a

Service Project Number	*Subject*	*RP No.*
	ARMY AIR FORCES PROJECT NUMBERS (Continued)	
AC-294	Radar jamming	RP-285 RP-338a
AC-294.12	Development of AN/APT-4 (165-780 Mc)	RP-338
AC-294.13	Development of AN/APT-8 (700 to 1200 Mc)	RP-244a RP-338
AC-294.17	Research and development of necessary antenna systems for equipment developed under Project AC-294	RP-138d, e, f RP-260a to d RP-303a, c, d, f, g, h RP-352
AC-294.18	Development of tuning adapter AN/APA-27	RP-380
AC-294.20	Research and development of airborne radar jamming systems for frequency range 1,000 to 5,500 Mc	RP-169a, b, c RP-295a RP-424a, b RP-425a, b RP-428 RP-435a, b RP-454 RP-455 RP-456 RP-472
	Ext. No. 1—Consultant service on AN/APQ-20	RP-284
AC-294.22	Propagation studies in radar jamming	RP-299a
AC-294.23	Research and development of low-powered (25-50 watts) tunable oscillators capable of being modulated by noise over a reasonably wide band and covering the frequency range 390-11,000 Mc	RP-169b RP-244b RP-295a RP-418 RP-430a, b, c
AC-294.27	Research and development of airborne radar jamming systems for frequency range 5,000 to 11,000 Mc	RP-221 RP-286a RP-403 RP-435a
AC-294.28	Investigation and development of improvements for existing airborne radar jammers and making recommendations thereon to the Air Technical Service Command	RP-338a, b
AC-294.29	Research and development of necessary airborne jamming systems for use against radio types of enemy proximity fuses	RP-117a, b, d
AC-295	Communications jamming	
AC-295.06	Research and development of necessary antenna systems for communications jamming equipment	RP-137 RP-260a to d
AC-295.07	Development of RF amplifier 500 watts (14-60 Mc)	RP-272a, b
AC-295.10	Study of communication jamming program and conducting of communications jamming effectiveness tests	RP-109a RP-441
AC-296	Deception devices	
AC-296.01	Research and development of deception devices (Chaff, Rope, Kites, etc.) from 30 to 33,000 Mc	RP-103a RP-257 RP-258b RP-406b, c, d, e, f
	Ext. No. 1—Misdirecting lobed radar by mechanical means	RP-406e
AC-296.04	Research and development of identification type Chaff for the S and X bands for use in ground vectoring of close support aircraft and in identification of single friendly aircraft for landing purposes	RP-103a
AC-297	Direction finder and special developments	RP-298a
AC-297.04	Research and development of airborne direction finding assembly AN/ARA-5 (1.75 to 30 Mc)	RP-404 RP-437 RP-444
AC-297.06	Research and development of airborne direction finding assembly (30-100 Mc)	RP-298d RP-444
AC-297.07	Investigation and development of improvements for existing airborne direction finding assemblies and making recommendations thereon to the Air Technical Service Command	RP-298a

SECRET

Service Project Number	*Subject*	*RP No.*
	ARMY AIR FORCES PROJECT NUMBERS (Continued)	
AC-298	Special countermeasures service	
AC-298.04	NDRC consultation and advisor service on airborne RCM procurement	RP-284 RP-314 RP-333 RP-431
AC-298.05	Ferret antennas and tests (radar and communications)	RP-315 RP-440a
AC-298.10	NDRC assistance in preparation of RCM (including AJ) training literature, training films, and actual training of selected RCM personnel	RP-317a RP-471
AC-298.11	Consultant service on radar tow targets	RP-349
AC-299	RCM test equipment	
AC-299.06	Research and development of special test equipment required for airborne radar jamming systems covering 1,000 to 11,000 Mc	RP-392 RP-479
AC-299.07	Research and development of special test equipment required for airborne microwave search receivers covering 1,000 to 33,000 Mc	RP-306c, d RP-416a RP-468 RP-469 RP-476
AC-300	NDRC consultation on airborne, RCM installations	RP-341
AC-300.02	Communication Ferret C-1.	RP-440a
	ARMY-NAVY PROJECT NUMBERS	
AN-8	Study of effective echoing areas of aircraft	RP-269
AN-17	Training films for anti-jamming	RP-317a
	NAVY PROJECT NUMBERS	
NA-102	Radar countermeasures (RCM program Division 15—general)	RP-394 RP-430a
NA-109	Jamming and anti-jamming radio controlled aircraft	RP-117a, b, d RP-278 RP-359 RP-360 RP-361 RP-362 RP-363 RP-382 RP-383 RP-384 RP-388 RP-389
NA-151	PB4Y-2 aircraft countermeasures equipment installation	RP-242
NA-156	X-band radar jammer and intercept receiver	RP-158a RP-221 RP-286a RP-403 RP-435a
NA-157	Radar search receivers and homing antennas	RP-302
NA-159	Incorporation of anti-jamming devices in radar equipment	RP-172 RP-223 RP-224 RP-225 RP-324 RP-411 RP-412 RP-413

Service Project Number	*Subject*	*RP No.*
	NAVY PROJECT NUMBERS (Continued)	
NA-180	To determine the possibility of identifying radar echoes from corner reflectors as contrasted to echoes from military targets	RP-258a RP-406j
	Ext. of: Production of 500 Angels for operational tests	RP-258a
NA-185	Study and improvement of anti-jamming features of radar systems AN/APS-3, AN/APS-4, AN/APS-6, AN/APS-15, and AN-APS-1	RP-225 RP-411 RP-412 RP-413
NA-187	Development of airborne jamming transmitters to cover range from 175 to 1200 Mc	RP-244a RP-285 RP-338
NA-189	Development of airborne S-band jammer	RP-169b RP-286c RP-295a RP-303c RP-414 RP-418 RP-424a, b RP-425a, b RP-435a, b RP-454 RP-455 RP-472
NA-199	Assistance on antenna problems involving radio and radar equipment for P4M aircraft	RP-137
NA-204	Consulting services on CU-43/APT & CU-44/APT Baluns	RP-273
NA-209	Development of stub antennas for use on high speed aircraft	RP-303e
NA-212	Development of faired-in antennas for naval aircraft	RP-260a, c, d RP-303f, i RP-484
NA-213	Determination of radiation patterns of naval aircraft	RP-137
NA-215	Consulting services on radar training set AN/TPQ-T2	RP-273
NA-217	Electronic test equipment developments—4,000-33,000 Mc	RP-446
NA-218	Anti-jamming of airborne radar equipment	RP-214a RP-324
NA-219	Anti-jamming study of AN/APS-4 radar equipment	RP-411
NA-220	Anti-jamming study of AN/APA-16 radar bombsight	RP-449
NA-221	Antenna patterns on SB2C and PB4Y-2 aircraft	RP-137
NA-224	Airborne jamming system for use with AN/APT-5 transmitter	RP-459
NA-230	Study of CM devices against proximity fuzes	RP-117a
NA-234	Airborne RCM operator's manual	RP-338b RP-477
NA-237	Consulting services on SA-44A/APR switch	RP-273
NO-193	Development of a jamming simulator for radar trainer Mark 1	RP-313
	Ext. of: Consultant service (BuShips) on manufacture of E1300 interference generator	RP-273
NO-217	Investigation of vulnerability of Pelican receiver to jamming	RP-355
NO-218	Training jammers for the radar equipment Mark 4 and Mark 12	RP-273 RP-364a
NO-219	Assistance to Navy on countermeasures training film-fire control radars, Mark 3 and Mark 4	RP-317a
NO-239	Development of model of the Video filter for anti-jamming device for radar equipment Mark 4	RP-214 RP-273
NO-273	Determination of vulnerability of Mark 31 radar system to countermeasures	RP-436
NO-278	Photographs illustrating anti-jamming of radar	RP-317b
NO-287	Consulting service on applying doppler to radar equipment Mark 4	RP-406
NP-2	Radar anti-jamming training course	RP-387
NR-112	Consulting services on analysis of enemy electronic devices	RP-478

SECRET

Service Project Number	*Subject*	*RP No.*
	NAVY PROJECT NUMBERS (Continued)	
NS-128	Development of means for jamming radio communication circuits	RP-109 RP-109a RP-115 RP-122 RP-148 RP-149 RP-150 RP-151 RP-152 RP-153 RP-154 RP-155 RP-199 RP-200 RP-232 RP-233 RP-234 RP-259 RP-260a, b, c RP-261b RP-307 RP-325 RP-358 RP-451
NS-179	Countermeasures—direction finder deception	RP-252
NS-189	Consultant service (Navy) for AN/APR-1, 2, 5, and 6	RP-273
NS-193	Recording mechanism for AN/APR-1 search receiver	RP-276
NS-200	Expendable jamming equipment	RP-132 RP-237
NS-202	Direction finding systems	RP-209 RP-271a to f RP-298a to f
NS-203	Development of monitoring and tracking indicator	RP-263
NS-204	Shipborne radar jamming	RP-138c RP-247 RP-275 RP-279 RP-305 RP-344 RP-394
NS-206	Jamming transmitter using Type ZP579 magnetron (consultant service)	RP-244a RP-316
NS-208	Consulting service on Type ZP579 magnetron	RP-244a
NS-209	Development of a practice jammer for low-frequency navy radar	RP-323
NS-213	Jamming of radio altimeters	RP-334
NS-214	Consulting service on shipborne radar jamming transmitter being developed by General Electric Company	RP-244a RP-335
NS-215	Development of antenna for use with ZP-590 magnetron jamming transmitter	RP-138
NS-216	Modulator for jamming transmitters, general application for training	RP-348
NS-217	General Electric Company CW magnetron ZP590	RP-244a
NS-218	General Electric Company CW magnetron ZP-584	RP-244a
NS-219	Airborne transmitter development project (using 150-watt magnetron tubes)	RP-244a RP-285 RP-338
NS-220	Consulting services on directional intercepter antennas for submarines	RP-138b RP-354
NS-241	Anti-jamming methods for shipborne radar	RP-214 RP-357

Service Project Number	*Subject*	*RP No.*
	NAVY PROJECT NUMBERS (Continued)	
NS-244	Consulting services of the Radio Research Laboratory to the Aviola Radio Corporation, Glendale, California	RP-298c
NS-251	Radar countermeasures equipments (Peter)	RP-156
NS-254	Consultant services on high-power jam transmitter for RCM application	RP-321
NS-258	Reduction of radar interference to communications systems	RP-189
NS-259	Consulting service on RRL Project M3000	RP-298c
NS-260	Dinamate equipment for operational tests in connection with CM against guided missiles	RP-250 RP-267 RP-303
NS-261	Redesign of the M3000 direction finder	RP-271b RP-273
NS-264	Type G1107 double tape window dispensers	RP-406b
NS-266	Model shop procurement of the M2600 direction finder	RP-271b
NS-278	Development of jammer tubes and circuits	RP-116 RP-159a, b RP-295d RP-321 RP-351 RP-391 RP-417b
NS-289	Development of MAS type jamming equipment	RP-395
NS-290	Consulting service on production of TS-109/SPR equipment	RP-273
NS-310	Development of 25 eight-way switches to be used with model TEA jamming equipment for GMCM use	RP-402a
NS-311	Development of jamming transmitter on S-band	RP-158a RP-169 RP-405 RP-415 RP-417a, b
	Ext. of: Consultant service in connection with production of AN/APQ-20 transmitter	RP-273
NS-312	Development of airborne system for homing on enemy airborne radar	RP-209
NS-313	Development of M3000 and M2300 antenna heads	RP-271d
NS-318	D2100 microwave receivers	RP-408a, b
	Ext. of: Consulting service in connection with modification of 25 AN/SPR-7A equipments	RP-273
NS-328	Study of antenna patterns of ship models	RP-261b RP-427
NS-333	Type M2900 antenna series in ranges 80-190 Mc and 750-1300 Mc	RP-138c
NS-340	Modification of AN/APT-4 countermeasures equipment	RP-338
NS-345	Modification of frequency range of U700, jamming signal generator	RP-364a
NS-348	Consultant services on model DBM direction finding equipment	RP-273
NS-393.05	Study of vulnerability of Navy FM equipment to jamming and development of anti-jamming measures	RP-334
NS-394.01	Development of low-power (up to 150 watts) vacuum tubes in the frequency range 60 to 12,000 Mc and consulting service as requested by BuShips	RP-244a, b RP-332 RP-393 RP-418 RP-430a, b RP-434 RP-439
NS-394.02	Development of medium-power (150-1500 watts) vacuum tubes in the frequency range 60 to 12,000 Mc and consulting service as requested by BuShips	RP-158a, b, c, d, f RP-244a RP-247 RP-434
NS-394.03	Development of high-power (above 1500 watts) vacuum tubes in the frequency range 60 to 12,000 Mc and consulting service as requested by BuShips	RP-116 RP-247 RP-351 RP-434

Service Project Number	*Subject*	*RP No.*
	NAVY PROJECT NUMBERS (Continued)	
NS-394.04	Design data and consulting service on modification of TDY transmitter to use QK-44 in frequency 2590-3430 Mc and antenna design	RP-138e RP-303c
NS-394.10	S-band jamming system—Range: 2700-3300 Mc (2400-4000 Mc)	RP-158a, b RP-303j, k RP-426 RP-435 RP-442 RP-457 RP-461a to c RP-462a, b
NS-394.14	General research on RCM antennas	RP-138c
NS-394.17	Construction of thirty (30) eight-way RF switches for use with the TDY system similar to those developed for the TEA equipment	RP-402a
NS-394.18	S-band antenna for countermeasures purposes	RP-303b
NS-394.19	Development of shipboard antennas for X-band countermeasures systems	RP-303
NS-394.20	Development of antenna for TDY countermeasures systems	RP-138c
NS-394.21	Antenna for AN/CPT-3 Coyote Buoy	RP-303e
NS-395.04	Jamming equipment for multiple signals of simultaneous occurrence	RP-389
NS-396.04	Consulting services on S-band Window for rockets	RP-273
NS-397.03	Development of a low-frequency antenna head for the AN/APA-17 direction finder	RP-298d
NS-397.07	Development of antenna head for model DBM-1 direction finding equipment for frequency range from 3000-12,000 Mc	RP-271d, e RP-298f
NS-397.08	Development of a radio-AN/APA-17 antenna head for range of 1000-4500 Mc	RP-271d
	Ext. of: Consultant service to BuShips in connection with production of M4500 antenna by Aviola Radio Corporation	RP-379
NS-397.10	AN/APA-48 direction finder equipments	RP-209
NS-398.07	Development of AN/ARQ-11 countermeasures equipment	RP-419b RP-421
NS-399.05	Radar CM manual Radseven	RP-480
	SIGNAL CORPS PROJECT NUMBERS	
SC-90	Radar search and warning receivers	
SC-90.01	Zero catcher I—RC-164 B	RP-147
SC-90.02	Automatic search receiver—AN/APR-2	RP-139
SC-90.03	Tuning unit for SCR-587—TU-56A	RP-141
SC-90.04	Tuning unit for SCR-587—TU-58B	RP-141
SC-90.05	Tuning unit for SCR-587—TU-57B	RP-141
SC-90.06	Tuning unit for SCR-587—TU-59A	RP-141
SC-90.07	Unit construction receiver—AN/APR-4	RP-144 RP-212
SC-90.08	Microwave search receiver—AN/APR-5	RP-135
SC-90.09	Microwave search receiver—AN/APR-6	RP-291
SC-90.10	Warning receiver—AN/APR-3	RP-287
SC-90.11	Development of recording assembly AN/APA-23	RP-276
SC-92	Radar anti-jamming and anti-jamming training equipment	
SC-92.01	Study of radar anti-jamming circuits	RP-214
SC-92.02	Anti-jamming for AN/APS-3	RP-225
SC-92.03	Anti-jamming for selected airborne radar sets	RP-277 RP-367 RP-368
SC-92.04	ASV jamming filter (SCR-521)	RP-222
SC-92.05	Development of trainer equipment AN/TPQ-T2	RP-160
SC-92.06	Development of microwave training generator A1700	RP-191
SC-92.07	Development of anti-jamming for SCR-268	RP-171

Service Project Number	*Subject*	*RP No.*
	SIGNAL CORPS PROJECT NUMBERS (Continued)	
SC-92.08	Integration methods for indicators	RP-318
SC-92.09	Development of training generator AN/UPT-T1	RP-180
SC-92.10	Radar anti-jamming training film	RP-317a
SC-92.11	Vulnerability study of radio set AN/TPL-1 with respect to electronic and window jamming	RP-453
SC-92.12	Vulnerability study of radio set SCR-545 with respect to electronic jamming	RP-475
SC-93	Communications anti-jamming and anti-jamming training equipment	
SC-93.01	Receiver vulnerability investigation	RP-189 RP-192 RP-397 RP-463 RP-464 RP-465 RP-466 RP-467
SC-93.02	Pulse communications jamming and anti-jamming studies	RP-123 RP-460
SC-93.03	Study of anti-jamming possibilities of super audible pulse	RP-229
SC-93.04	Research and development of protected communication system	RP-124
SC-93.05	Studies of jamming and anti-jamming of radio telegraphy	RP-109a RP-159
SC-93.06	Studies of AM vs. FM from anti-jamming standpoint	RP-131
SC-94	Radar jamming	RP-447
SC-94.01	Mandrel AN/APT-3	RP-163
SC-94.02	Dina AN/APT-1	RP-309
SC-94.03	Power amplifier for AN/APT-1 and AN/APT-3 (AN/AM-14/APT)	RP-218
SC-94.04	Power amplifier for AN/APT-1 (AN/AM-18/APT)	RP-329
SC-94.05	Rug AN/APQ-2	RP-164
SC-94.06	Carpet AN/APT-2	RP-165
SC-94.07	High-power Carpet AN/APQ-9	RP-166 RP-166a
SC-94.08	Carpet Sweeper AN/APQ-1	RP-167
SC-94.09	Carpet IV AN/APT-5	RP-336
SC-94.11	Maggie AN/APT-7 (90 to 400)	RP-285 RP-338
SC-94.12	Maggie AN/APT-4 (310 to 750)	RP-244a RP-285 RP-338
SC-94.13	Maggie AN/APT-8 (600 to 1000)	RP-244a RP-285 RP-338
SC-94.14	Mobile jammer for AN/MPQ-1	RP-100
SC-94.15	Special antenna development	RP-138
SC-94.16	Research and development of electronic noise sources	RP-181 RP-187a, b RP-196 RP-311
SC-94.17	Research and development of antennas for use with jammers developed under SC-94	RP-107a RP-138 RP-260a, b, c RP-345 RP-352
SC-94.18	Lock-on jamming attachment for AN/APT-4 and AN/APQ-2	RP-380
SC-94.19	Development of a ground based mobile barrage jamming transmitter using a tunable magnetron	RP-116 RP-321 RP-340 RP-351

SECRET

Service Project Number	*Subject*	*RP No.*
	SIGNAL CORPS PROJECT NUMBERS (Continued)	
SC-94.20	Development of radar jamming set AN/APT-9 (1000-2200 Mc)	RP-169 RP-204 RP-407 RP-425a, b RP-428 RP-430a
SC-94.21	Development of radar jamming equipment (2000-3500 Mc)	RP-407 RP-414 RP-424 RP-425a, b RP-430a
SC-94.22	Propagation studies in radar jamming	RP-299a, b
SC-94.23	Research and development of low-powered (25-50 watt) tunable oscillators (390-11,000 Mc)	RP-169b RP-244b RP-295a RP-418 RP-430a, b, c
SC-94.24	Development of a 10 kw tunable magnetron (and transmitter circuit work)	RP-116b RP-321 RP-351
SC-94.25	Development of a ground-based radar jamming equipment using 1-kw tunable magnetrons (200-4000 Mc)	RP-158a, b, c, d, f RP-303j, k RP-405 RP-417a, b RP-442 RP-457 RP-461a, b, c RP-462a, b
SC-95	Communications jamming	
SC-95.01	Development of FM jammer (Jackal II)	RP-150
SC-95.02	Dinamate AN/ARQ-8	RP-250 RP-267
SC-95.03	Development and procurement of Cigar AN/MRT-1	RP-356a, b
SC-95.04	Chick AN/CRT-2	RP-132
SC-95.05	Wave propagation study	RP-149
SC-95.06	Research and development of broad-band antenna for communications jamming equipment	RP-137 RP-259 RP-260a
SC-95.07	Development of radio frequency amplifier AM-33/ART	RP-344
SC-95.08	Development of radio frequency amplifier 500 watts (14-60 Mc)	RP-272a, b
SC-95.09	Airborne spot jammer system study	RP-358
SC-95.10	Communications jamming effectiveness tests	RP-109 RP-109a RP-451
SC-95.11	Development of listening through and jammer alignment system	RP-122
SC-95.12	Development of 50 kw radio jamming system (20-70 Mc) (AN/GRQ-1)	RP-420a, b
SC-95.13	Modification kit for radio set AN/MRT-1	RP-356c
SC-95.14	Research and development of radio set AN/ARQ-11	RP-419a RP-421
SC-95.16	Countermeasures against radio navigational aids	RP-422 RP-445
SC-96	Deception devices	
SC-96.01	Diffuse confusion reflectors (Window)	RP-103a RP-257 RP-406b, c, d, e, f, g
SC-96.02	Research and development of corner reflectors (Angels)	RP-258b
SC-96.03	Window filler for mortar shell	RP-103b
SC-96.04	Simulation of radio powered VT fuses	RP-117a

Service Project Number	*Subject*	*RP No.*
	SIGNAL CORPS PROJECT NUMBERS (Continued)	
SC-97	Direction finders and special developments	
SC-97.01	Homing and direction finding AN/APQ-14	RP-188
SC-97.02	Direction finding antenna AN/APA-24 (100-480 Mc)	RP-298a
SC-97.03	Direction finding system for 250 to 800 Mc (AN/APA-17)	RP-298
SC-97.04	Research and development of airborne direction finding antenna AN/ARA-5 (1.75-30 Mc)	RP-404 RP-437 RP-444
SC-97.05	Research and development of airborne direction finding methods (800-3000 Mc)	RP-298
SC-97.06	Research and development of airborne direction finding antennas (30-100 Mc)	RP-298b RP-404 RP-444
SC-98	Special countermeasures services	
SC-98.01	Construction of synthetic giant wurzburg	RP-179
SC-98.02	Equivalent echoing areas of aircraft	RP-269
SC-98.03	NDRC consultation on airborne RCM Installations	RP-341
SC-98.04	NDRC consultation and advisor service on airborne RCM procurement	RP-284 RP-314 RP-333 RP-431 RP-433
SC-98.05	Ferret antennas and tests	RP-315
SC-98.06	RCM catalog and text	RP-HAC
SC-98.07	Research and development of countermeasures vs. radio controlled missiles	RP-361 RP-362 RP-382 RP-383 RP-384 RP-388 RP-389
SC-98.08	Magnetic countermeasures investigation	RP-386
SC-98.09	Research of countermeasures against proximity fuses	RP-117a, c, d
SC-98.10	RCM against radar blind bombing	RP-474
SC-98.98	NDRC consultation and advisory service on procurement of ground-based RCM equipment	RP-314 RP-470
SC-99	RCM test equipment	
SC-99.01	Test equipment for search receivers TS-47/APR	RP-195
SC-99.02	Wavemeter for AN/APT-1 and AN/APT-3 TS-99/AP	RP-245
SC-99.03	Wavemeter for AN/APQ-2 TS-53/AP	RP-290
SC-99.04	Spectrum analyzer TS-54/AP	RP-175
SC-99.05	Pulse generator (RRL F-2200)	RP-289
SC-99.06	Research and development of special test equipment required for airborne jamming systems (1000-3500 Mc)	RP-385 RP-392 RP-416

DIVISION 15 RESEARCH PROJECT NUMBERS AND ASSIGNMENTS

Identification of Division 15 projects was accomplished by the assignment of an RP number to each project. The projects were then assigned to a Division 15 Contractor or, in some cases, different phases of a given project was assigned to different contractors.

The following list gives the RP number of each Division 15 project and the OEMsr number of the contract to which it was assigned. The contractor's identity may be determined by cross-reference to Contract Numbers, pages 498–500.

RP Number	*Subject*	*Contract Number*
100a	High-power ground jammer (Tuba)	OEMsr-411
100b	Development of a prototype model of a 50 kw ground jammer	OEMsr-411
100c	Tuba production model	OEMsr-411
103a	Deception and confusion reflection (Chaff)	OEMsr-411
103b	Window filler for mortar shells	OEMsr-411
106	Homing on jammers (Fanny)	OEMsr-411
107	Characteristics of cone antennas	OEMsr-411
107a	Theory of impedance matching	OEMsr-411
107b	Theoretical antenna studies	OEMsr-411
107c	Waveguide components (3000-10,000 Mc)	OEMsr-411
109	Communication jamming effectiveness tests	OEMsr-966
109a	Vulnerability of enemy communications receivers	OEMsr-1024
110	Pulse repeater (moonshine)	OEMsr-411
112	ABL-15 version of Boozer (AN/APR-3)	OEMsr-411
115	Study of communication jamming (Jostle)	OEMsr-966
116	High power tunable CW magnetrons	OEMsr-931
117	Wide-band regenerative amplifier	OEMsr-411
117	Proximity fuses from CM viewpoint	OEMsr-411
117a	Proximity fuses countermeasures	OEMsr-1305
117b	Airborne PF jammer	OEMsr-1305
117c	Ground-based PF jammer	OEMsr-1305
117d	Search receiver for proximity fuses	OEMsr-1305
122	Listening through and jammer alignment systems	OEMsr-993
123	Pulse communication jamming and anti-jamming studies	OEMsr-895
124	Protected communication system	OEMsr-937
126	Vulnerability of Loran to radio countermeasures	OEMsr-411
128	Study of radar AJ circuits	RL under NDRC Div.14
131	AM vs. FM from AJ viewpoint	OEMsr-895
132	Expendable communications jammer (Chick)	OEMsr-940
135	Microwave search receiver (1000-3100 Mc) (AN/APR-5)	OEMsr-411
135a	X-band coaxial mixers for AN/APR-5 receiver	OEMsr-411
136	Pimpernel	OEMsr-653, 867
	Pimpernel modification	OEMsr-1045
137	Airborne antenna radiation patterns	OEMsr-759
138	Design of specific antennas	OEMsr-411
139	Autosearch receiver (90-1000 Mc) (AN/APR-2)	OEMsr-411
140	Blinker panoramic receiver	OEMsr-867
140	Dustpan autosearch receiver	OEMsr-411
140	Band-spread blinker	OEMsr-1045
141	Tuning units for ARC-1, SCR-587, APR-1, APR-4 and SPR-1	OEMsr-411
144	Unit construction receiver (AN/APR-1, -4, AN/SPR-1)	OEMsr-411
144a	Modification of AN/APR-1 to increase output on pulsed signals	OEMsr-411
144b	Conversion of AN/APR-1 i-f amplifier for spot jamming	OEMsr-411
145	Superheterodyne with pre-selection	OEMsr-411
146	R-C receiver	OEMsr-411
147	Zero-Catcher I (RC-164B)	OEMsr-411
148	Conversion of transmitters into jammers	OEMsr-966
149	Wave propagation studies	OEMsr-966
150	Barrage jammer (Jackal) (AN/ARQ-2)	OEMsr-940
	Airborne barrage jamming system	OEMsr-966
151	Research on barrage jammers (Pup)	OEMsr-966
152	Study of spark jammer	OEMsr-940
153	Conversion of WE ATR transmitter to jammer	OEMsr-940
154	Dina for communication jamming	OEMsr-940

RP Number	*Subject*	*Contract Number*
155	Electro-mechanical FM jammer	OEMsr-940
156	Electric pulse repeater Peter	OEMsr-931
	Installation and operation of Peter	OEMsr-1045
157	Investigation of persistent echoes from shells	OEMsr-931
158a	Moderate power tunable CW magnetrons (Piccolo)	OEMsr-1019
	X-band tunable CW magnetron (Type L-104)	
158b	Moderate power tunable CW magnetron	OEMsr-1357
158c	1-kw CW tunable magnetrons	OEMsr-1430
158d	1-kw split anode magnetron	OEMsr-1043
158e	1-kw CW tunable magnetrons	OEMsr-1456
158f	1-kw CW tunable magnetrons (Piccolo)	OEMsr-931
159	Jamming and anti-jamming of radio telegraphy	OEMsr-936
160	Signal generator for 90-250 Mc (AN/TPQ-T2)	OEMsr-923
161	Carrier-less noise transmitter (Dina I)	OEMsr-411
162	100-Mc transmitter	OEMsr-411
163	Mandrel transmitter (AN/APT-3)	OEMsr-411
	Modification of AN/APT-3	OEMsr-1045
164	Rug transmitter (AN/APQ-2)	OEMsr-411
165	Carpet I (AN/APT-2)	OEMsr-411
	Carpet I modification	OEMsr-1045
165a	Modification of AN/APT-2 (Carpet IA)	OEMsr-411
165b	Film on Carpet spot jamming (AN/APT-2)	OEMsr-411
166	Carpet III (AN/APQ-9)	OEMsr-411
166a	Oscillator for converting APQ-1 to 145-350 Mc	OEMsr-411
167	Carpet Sweeper I (460-600 Mc) (AN/APQ-1)	OEMsr-411
	Carpet Sweeper I (460-600 Mc)	OEMsr-1045
168	VHF oscillators (L-3 Tube)	OEMsr-411
169	Microwave jamming	OEMsr-411
	Microwave jamming transmitter	
169a	Oscillator research (1000-2000 Mc) (AN/APQ-21)	OEMsr-411
169b	S-Band tunable CW magnetron	OEMsr-411
169c	R-F wattmeter for 1000-3000 Mc range	OEMsr-411
170	Zero Catcher homing device	OEMsr-411
171	Susceptibility to jamming of the SCR-268 radar equipment	OEMsr-411
172	Vulnerability of SCR-617/ASG	OEMsr-411
173	Microwave oscillator (1000-3300 Mc)	OEMsr-411
174	Signal generator (1000-3000 Mc)	OEMsr-411
175	Spectrum analyzer (20-150 Mc & 90-1000 Mc) (TS-54/AP)	OEMsr-411
176	Video spectrum analyzer	OEMsr-411
177	Photography of cathode-ray tubes	OEMsr-411
178	Power supplies (400-2600 cps)	OEMsr-411
179	Synthetic giant Wurzburg	OEMsr-411
180	Carpet practice jammer	OEMsr-411
181	Theoretical study of noise	OEMsr-411
182	Study of pulse jamming characteristics of pulses	OEMsr-411
183	Crystal test equipment	OEMsr-411
184	RF power measuring devices	OEMsr-867
185	Wide range wavemeter (80-1000 Mc)	OEMsr-867
186	Basic study of jamming	OEMsr-411
187	Wideband video transformers	OEMsr-411
187a	Study of noise sources	OEMsr-411
187b	Wideband transformers for noise	OEMsr-411
188	Receiver for radar homing missile (Moth) (AN/APQ-14)	OEMsr-411
189	Vulnerability of communication receivers	OEMsr-1024
190	Monitoring of enemy signal (See Saw)	OEMsr-966
191	Jamming signal generator (2400-3700 Mc)	OEMsr-411
192	Development of an externally modulated signal generator for range 20-40 Mc	OEMsr-1005
193	Search receiver for PF signals	OEMsr-1045
194	Protected communication system	OEMsr-937
195	Test oscillator for 40-500 Mc (TS-47/APR & TS-109/SPA)	OEMsr-923
196	Electronic noise sources	OEMsr-1060

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RP Number	*Subject*	*Contract Number*
197	High-power communication jammer (Cigar)	OEMsr-1107, 411, 1045
198	Expendable broadcast transmitter (Hen)	OEMsr-895
199	Airborne communication jammer (Pad) (AN/ART-2)	OEMsr-940
200	Power amplifiers for ARQ-10 (500 watts 1.3-45 Mc)	OEMsr-1275
202	Microwave autosearch receiver	OEMsr-411
203	Wideband electronic FM	OEMsr-411
204	Oscillator research in L-band	OEMsr-411
205	GL 449 oscillator	OEMsr-411
207	Jamming signal generator	OEMsr-411
208	100/200 Mc transmitter	OEMsr-411
209	Homing receiver attachments (Tail)	OEMsr-411
210	Pulse repeater (Stardust)	OEMsr-411
212	Microwave tuning unit for APR-1, -4	OEMsr-411
213	Study of propeller modulation	OEMsr-411
214	Study of radar AJ circuits	OEMsr-411
214a	Polarization cancellation system for AJ	OEMsr-411
215	Super-regenerative receiver	OEMsr-411
217	Study of frequency-modulated oscillators	OEMsr-411
218	100-watt power amp. (85-150 Mc) (AM-14/APT)	OEMsr-411
	Modification of AM-14/APT for LF	OEMsr-411
221	X-band field test jammer	OEMsr-411
222	Vulnerability of SCR-521A/ASVC	OEMsr-411
223	Vulnerability of ASB radar	OEMsr-411
224	Vulnerability of FD radar	OEMsr-411
225	Vulnerability of ASD-1 (AN/APS-3) radar (AN/APS-1)	OEMsr-411
226	Vulnerability of SCR-520 radar system	OEMsr-411
227	AJ features of 7 unit printer	OEMsr-895
228	AJ features of tape facsimile	OEMsr-895
229	AJ possibilities of impulse and time code signalling systems	OEMsr-895
230	Synchronous tracking (meandering)	OEMsr-895
231	AJ features of status change device	OEMsr-895
232	Double side-band Dina for jamming	OEMsr-940
233	Audio noise sources (Gaston)	OEMsr-966
234	Non-coherent pulses for jamming	OEMsr-940
235	Jamming efficiency tests	OEMsr-940
237	Expendable radar jammers	OEMsr-411
239	Coaxial diode	OEMsr-867
240	Multi-channel barrage jammer	OEMsr-867
241	Signal generators	OEMsr-867
242	Albatross I	OEMsr-411
243	Constriction oscillator as noise source	OEMsr-931
244a	Low-power tunable CW magnetrons (Flute)	OEMsr-931
244b	X-band CW tunable magnetrons	OEMsr-1043
245	Heterodyne frequency meter (55-250 Mc) (TS-99/AP)	OEMsr-411
246	Orange Squeezer	OEMsr-411
247	Sealed-off resnatron	OEMsr-1034
248	Microwave spark jammer	OEMsr-411
249	Long distance sky wave jamming	OEMsr-778, 966
250	Receiver for tuning Dina (Mate) (AN/ARQ-8)	OEMsr-411
251	Miscellaneous microwave jamming devices	OEMsr-411
252	Direction finding deception (Blanket)	OEMsr-895
253	Infradyne tuning unit for SRC587/ARC-1	OEMsr-411
257	Confusion reflectors (Rope)	OEMsr-411
258	Corner reflectors (Angels)	OEMsr-931
258a	Confusion reflectors (Angels)	OEMsr-411
258b	Confusion reflectors (Kites)	OEMsr-411
259	Communication antenna studies	OEMsr-966
260a	Development of broadband antennas	OEMsr-895
260b	Development of broadband, sleeve type, streamlined antennas	OEMsr-895
260c	Broadband antennas for high-speed airplanes	OEMsr-895

RP Number	*Subject*	*Contract Number*
260d	Development of faired-in antennas	OEMsr-895
261	Investigation of antenna reference material	OEMsr-867
	Antenna system for Moth	OEMsr-867
	Long-wire antennas	OEMsr-867
	Wide-band low-frequency antennas	OEMsr-867
	Pattern measurement of shipborne antennas	OEMsr-867
262	Beaver	OEMsr-411
263	Monitoring and tracking of CW signals	OEMsr-895
264	Autosearch tuning unit (25-50 Mc)	OEMsr-867
	Modifications of communications autosearch receiver (Blinker)	OEMsr-1045
266	931 Tube field test set	OEMsr-411
267	Airborne suppressed-carrier noise jammer (25-104 Mc) AN/ARQ-8	OEMsr-411
269	Equivalent echoing areas of aircraft	OEMsr-759
270	Crystal rectifier as peak voltmeters	OEMsr-923
271a	Shipborne DF system heads	OEMsr-411
271b	DF antenna for radar search	OEMsr-411
271c	Directional antenna for radar search receiver	OEMsr-411
271d	Microwave DF antenna (CFH-6613, AS-186/APA-17)	OEMsr-411
271e	X-band antenna head for DBM DF system	OEMsr-411
271f	Submarine DF for radar frequencies	OEMsr-411
271g	Low-frequency DF antenna spinner for DBM	OEMsr-411
272a	Power amplifier (500 watts, 14-60 Mc) (AM-66/ARxr)	OEMsr-940
272b	Field tests of AM-66/ARxr amplifier	OEMsr-966
273	Consultant service (Navy) for APR-1, APR-2, APR-5 and APR-6	OEMsr-411
275	Shipborne jamming transmitter using ZP-522 tubes (AN/SPT-6)	OEMsr-411
276	Recorder for AN/APR-1, -4 & AN/SPR-1 receiver (AN/APA-23)	OEMsr-411
277	Vulnerability of the SCR-717B radar	OEMsr-411
279	Ground-based antenna for 90-210 Mc	OEMsr-411
280	Variable frequency microwave radar	RL under NDRC Div. 14
281	Consultant service to Radiation Laboratory on tunable microwave radar system	OEMsr-411
283	Paint to absorb electromagnetic radiation	RL under NDRC Div. 14
284	Consultant service to the Army on the procurement of airborne RCM equipment	OEMsr-411
285	L-band magnetron transmitter research	OEMsr-411
286	Search receiver research	OEMsr-411
287	Zero Catcher II	OEMsr-411
288	Early warning receiver research	OEMsr-411
289	Carpet Tester (TS-52/APQ-1)	OEMsr-411
290	Carpet Checker (TS-53/AP)	OEMsr-411
291	Microwave search receiver (3000-6000 Mc) (APR-6)	OEMsr-411
292	Test oscillator (2500-3500 Mc)	OEMsr-411
293	Alignment indicator for RF amplifier (TS-92/AP)	OEMsr-411
	Twin peaking alignment device 550 kc–10 Mc	
294	Frequency standard and monitor for mandrel	OEMsr-411
295a	S-band tunable magnetrons	OEMsr-411
295b	Investigation of Sylvania SD-849 tube	OEMsr-411
295c	Study of magnetrons	OEMsr-411
295d	Investigations of low-power squirrel-cage S-band magnetrons	OEMsr-411
297	Receiver (Lobster) for tail	OEMsr-411
298	Development of DF methods	OEMsr-411
299a	RCM wave propagation considerations	OEMsr-411
299b	Propagation studies	OEMsr-411
299c	Experimental determination of formation factor	OEMsr-411
301	Simulated CM unit installation	OEMsr-411
302	Albatross II	OEMsr-411
303	Horizontal and circularly polarized RCM antennas	OEMsr-411
305	Methods of modulating oscillators in L band	OEMsr-411
306	Development of laboratory instruments	OEMsr-411
307	Electronic tuning for panoramic reception	OEMsr-1138
308	L-band ground jammer	OEMsr-411

SECRET

RP Number	*Subject*	*Contract Number*
309	Airborne suppressed carrier noise jammer (Dina II) (AN/APT-1)	OEMsr-411
	High frequency Dina, Dinamate transmitter	
310	Antenna pattern measuring equipment	OEMsr-867
311	Study of noise sources	OEMsr-1176
312	Oscillator and modulator for Carpet IV	OEMsr-867
313	Jamming simulator for Mark I radar trainer (TS-109SPA)	OEMsr-411
314	Advisor service to the Army Signal Corps on RCM procurement	OEMsr-411
315	Ferret installation studies	OEMsr-411
316	Consultant service (GE) shipboard jamming transmitter	OEMsr-411
317a	AJ training films	OEMsr-411
317b	J and AJ photographs on Mark IV radar	OEMsr-411
318	Integration methods for indicators	OEMsr-411
319	Vacuum tube field pattern measurements	OEMsr-867
320	Studies of gas discharge tubes	OEMsr-867
321	High-power L-band transmitters	OEMsr-411
323	Practice jammer for low-frequency Navy radar (AN/UPT-T4)	OEMsr-411
324	Vulnerability of Navy airborne radar systems	OEMsr-411
325	Search receivers and analyzers for pulse communications	OEMsr-895
326	Communications jamming on maneuvers	OEMsr-966
327	Jammer frequency setting	OEMsr-411
328	Synthetic German AI transmitter	OEMsr-411
329	Power amplifier (50 watts 140-210 Mc) (AM-18/APT)	OEMsr-411
331	Wide-band oscilloscope	OEMsr-867
	RF power meter and standing wave detector	
332	Oscillator tube research (X band)	OEMsr-1222
333	Consultant service (Army SC) on production of Chaff	OEMsr-411
334	Vulnerability of radio altimeters to jamming and development of AJ measures	OEMsr-1305
335	Consultant service on shipboard transmitters	OEMsr-411
336	Airborne barrage jammer (Carpet IV) (AN/APT-5)	OEMsr-411, 867
338	Air Broadloom III (AN/APT-4)	OEMsr-411
	Air Broadloom II (AN/APT-7)	
	Development of AN/APT-8 transmitter	
	L-band magnetron transmitter (Air Broadloom III)	OEMsr-1045
338a	Investigation of bandwidth and relative jamming effectiveness of various transmitters	OEMsr-411
338b	Study of transmitters for spot jamming	OEMsr-411
339	Radar jamming system—Beaver III	OEMsr-411
340	10-kw ground or ship magnetron transmitter	OEMsr-411
341	Consultant service (ARL) on RCM aircraft installations	OEMsr-411
342	High frequency Dinamate Receiver (Dinamate II)	OEMsr-411
343	Installation of SCR-648 radar	OEMsr-411
344	Power amplifier (100 watts, 35-100 Mc) (AM-33/APT)	OEMsr-411
345	Consultant service (SC) on RCM antennas	OEMsr-895
346	100-watt jammer (90-400 Mc)	OEMsr-411
347	Spectrum analyzer (100-1400 Mc)	OEMsr-931
348	Training modulator for jamming transmitter (RF-9/UPT)	OEMsr-411
349	Consultant service (AAF) on radar tow targets	OEMsr-411
350	Fundamental studies of cavity oscillators	OEMsr-411
351	10-kw magnetron tube development	OEMsr-747
352	Antennas for horizontal polarization at UHF	OEMsr-895
353	Resnatron development	OEMsr-747
354	Consultant service to the Navy—re: broadband receiving antenna for submarine uses	OEMsr-411
355	Vulnerability of RHB (Pelican) receiver	OEMsr-411
356a	15-kw communications jammer (38-52 Mc) AN/MRT-1 (Cigar)	OEMsr-1309, 1310
356b	Noise modulation for Cigar	OEMsr-940
356c	Modification kits for Cigar (MX255/MRT-1)	OEMsr-1310
357	Vulnerability of Mark 12 radar	OEMsr-411
358	Airborne spot jammer system study	OEMsr-966
359	Automatic search jammer (Broom)	OEMsr-1305
360	Automatic-search jammer (Beagle)	OEMsr-1305
361	Signal recording equipment (ARQ-12, SRQ-2)	OEMsr-1305
362	Signal repeating jammer (Piano)	OEMsr-1305

RP Number	*Subject*	*Contract Number*
363	Panoramic receiver (Panther)	OEMsr-1305
364a	Training jammer for Mark IV radar	OEMsr-411
364b	Low-frequency jamming signal generator	OEMsr-411
367	Vulnerability of the SCR-720 radar	OEMsr-411
368	AJ study of AN/APG-1 radar system	OEMsr-411
378	Investigation of 1-kw resnatron	OEMsr-411
379	Consultant service (Navy) on procurement of DF equipment	OEMsr-411
380	Automatic search and lock-on jamming system (Automat) (AN/APA-27)	OEMsr-411
381	Modification of ARC-1 and SCR-587 receiver	OEMsr-411
382	Studies of antennas and associated elements	OEMsr-1305
383	Fundamental jamming and anti-jamming studies	OEMsr-1305
384	Vulnerability of controlled devices	OEMsr-1305
385	Jamming signal generator (2700-3300 Mc)	OEMsr-411
386	Magnetic countermeasures investigation	OEMsr-1305
387	Navy AJ instructor training course	OEMsr-411
387a	AN/APA-48 training program	OEMsr-411
388	1-kw amplifier	OEMsr-1305
389	Multiple-channel exciter system for GM CM (AN/SRQ-1)	OEMsr-1305
391	Consultant service (Navy) on the development of a high-powered shipborne transmitter	OEMsr-411
392	Spectrum analyzer (10-3500 Mc)	OEMsr-931
394	5-kw plane Parallel tetrode (L-201)	OEMsr-931
395	Medium power GM jammer (MAS)	OEMsr-1305
397	Evaluation of communication transmitter performance	OEMsr-1024
398	Research on 1-kw transmitter	OEMsr-411
399	Antenna impedance measurements	NDrc-100
402a	RF switches (CLU-24314)	OEMsr-1305
402b	4-way coaxial switches	OEMsr-1305
403	X-band transmitter research	OEMsr-411
404	Model study of airborne direction finders	NDCrc-100
405a	1-kw ground jammer	OEMsr-411
405b	Wide band coaxial line	OEMsr-411
406	AJ methods for Window	OEMsr-411
406a	Study of radar AJ circuits	OEMsr-411
406b, f	Window dispensing devices	OEMsr-411
406c	Window pilot factory	OEMsr-411
406d	Confusion reflectors (basic research)	OEMsr-411
406e	Theory of reflectors	OEMsr-411
406g	Radiation measurements of Window	OEMsr-867
406j	Detection of radar decoy reflectors	OEMsr-411
407	Investigation of negative-grid high-frequency tubes	OEMsr-411
408a	Wide range, tunable direct detection receiver (Spud I) (AN/APR-7A)	OEMsr-411
408b	Wide range, tunable direct detection receiver (Spud II) (AN/APR-8)	OEMsr-411
408c	Wide range, tunable direct detection receiver (Spud III)	OEMsr-411
409	RF power indicator	OEMsr-411
410	Trailing coaxial dipole antenna (Stingeree)	OEMsr-966
411	AJ investigation of AN/APS-4	OEMsr-411
414	Airborne S-band jammer	OEMsr-411
415	Shipborne S-band klystron jammer	OEMsr-411
416a	Microwave test oscillator	OEMsr-411
417a	Investigation of L-band Piccolo-series magnetron	OEMsr-411
417b	Investigation of S-band magnetron	OEMsr-411
418	Low-power S-band CW tunable magnetron	RL under NDRC Div. 14
419a,b	1.5-kw airborne GM jammer (AN/ARQ-11, SRQ-11)	OEMsr-1305
420a	Modification of FM transmitter (AN/GRQ-1)	OEMsr-1305
420b	Antenna system for GRQ-1	OEMsr-1305
421	Development of MAS type receiver (AN/ARQ-11)	OEMsr-1305
422	Radio navigational aids—CM Study	OEMsr-966
424	Airborne S-band magnetron transmitter (AN/APQ-20)	OEMsr-411
425a	Panoramic unit (Panda) (AN/APA-41)	OEMsr-411

RP Number	*Subject*	*Contract Number*
425b	Panoramic unit (Panda)	OEMsr-1305
426	Consultant service (Navy) on the Elephant jamming system	OEMsr-411
427	Ground planes for antenna model measurements	OEMsr-759
428	Airborne jammer for S band (1000-2500 Mc)	OEMsr-411
429	Army RCM training courses	OEMsr-411
430a	S-band amplifier tubes 25-watt CW tunable magnetrons	OEMsr-931
430b	Low-power CW tunable magnetrons	OEMsr-1456
431	Consultant service (Army) on RCM procurement	OEMsr-1305
432	Meteorological observations for propagation studies	OEMsr-1305
433	Consultant service (Army) on tube procurement	OEMsr-931
434	Consultant service (Navy) on tube procurement	OEMsr-1019
435a	Single signal receivers	OEMsr-411
435b	Tuning unit for single signal receivers	OEMsr-411
435c	X-band tuning unit for single signal receivers	OEMsr-411
436	Vulnerability of control equipment Mark II (Bat)	OEMsr-411
437	Airborne direction finder flight testing	OEMsr-936
438	Spec. broadband signal repeating system	OEMsr-411
439	Consultant service on vacuum tubes 2K48 (1429CT-8) and 2K49 (1429CT-9)	OEMsr-1222
440a	Communications Ferret systems study	OEMsr-966
440b	Ferret systems design	OEMsr-966
441	Communication countermeasures studies	OEMsr-966
442	Assistance to Radiation Laboratory on AEW project	OEMsr-411
442a	Intercept receiver filters	OEMsr-411
442b	Microwave filter development	OEMsr-411
443	General improvements for existing search receivers	OEMsr-411
444	Airborne direction finding system (1.5–100 Mc)	OEMsr-1458
445	Instrumental susceptibility to countermeasures of navigation direction finders	OEMsr-1458
446	Study of test equipment	OEMsr-411
447	AJ applications to receivers	OEMsr-411
448	Blanking circuit for search receivers (Silent Knight)	OEMsr-411
449	AJ investigation of the AN/APA-16 as used with APS-4	OEMsr-411
450	Consultant service to Psycho-Acoustical Laboratory	OEMsr-1024
451	Effect of receiver circuits on susceptibility to jamming	OEMsr-1024
452	AJ investigation of APQ-5B	OEMsr-411
453	Evaluation tests on TPL-1	OEMsr-411
454	S-band spot jamming system (AN/APQ-20, -27)	OEMsr-411
455	300 to 2500 Mc spot jamming system	OEMsr-411
457	Elephant system, design, and assembly	OEMsr-411
458	200 Mc GL airborne jamming system	OEMsr-411
459	1100 Mc A1 jamming system	OEMsr-411
460	Vulnerability to jamming of pulse communication system	OEMsr-895
461a	1-kw shipborne transmitter for Elephant jamming system	OEMsr-411
461b	Study of operating characteristics of the 6J21 (612) tube for use in the Elephant jamming system	OEMsr-411
461c	Low-frequency oscillator for Elephant jamming system	OEMsr-411
462a	Receiver for Elephant jamming system	OEMsr-411
462b	P.R.F. and pulse width indicator	OEMsr-411
462c	Unit shipborne receiver	OEMsr-411
462d	X-band head for Elephant receiver	OEMsr-411
463	Development of a frequency modulator for the 605B standard signal generator	OEMsr-1005
464	P-551 amplifier	OEMsr-1005
465	Signal generator for 20-156 Mc	OEMsr-1005
466	P-553 signal generator	OEMsr-1005
467	Frequency multiplier for P-519 signal generator	OEMsr-1005
468	Microwave signal generator	OEMsr-411
469	Microwave standard signal generator	OEMsr-411
470	Consultant service (Army) on the procurement of ground-based RCM equipment	OEMsr-411
471	Ferret DF antenna trainer	OEMsr-411
472	RF connectors	OEMsr-411
473	Audio-frequency amplifier	OEMsr-411

RP Number	*Subject*	*Contract Number*
474	RCM for radar blind bombing	OEMsr-411
475	AJ study of SCR-545	OEMsr-411
476	Spark excited signal generators	OEMsr-411
477	Airborne RCM operator's manual	OEMsr-411
478	Assistance to the operations research group	OEMsr-411
479	Microwave wattmeter	OEMsr-411
480	Rad Seven—radar countermeasures manual	OEMsr-411
481	Miscellaneous interim antennas	OEMsr-411
483	Model antenna pattern measurements	OEMsr-1305
484	Development of faired-in antennas for high-speed aircraft	OEMsr-1305
974	Advanced service base	OEMsr-1045
975	Communications deception device	OEMsr-1045
976	Emergency aid to 9th AAF on high-frequency communications	OEMsr-1045
977	Investigation of enemy jamming	OEMsr-1045
979	Guided missile investigation	OEMsr-1045
980	Receivers for spot jamming	OEMsr-1045
981	Window activities in ETO	OEMsr-1045
982	Ground search band	OEMsr-1045
983	Reduction of interference from CSFR-TDY transmitter	OEMsr-1045
984	Study of airborne antennas	OEMsr-1045
985	Naval investigational program	OEMsr-1045
986	Installation of Jackal (ART-3)	OEMsr-1045
987	Barrage jamming installations	OEMsr-1045
988	Ground-based antenna for communications AJ (3-6 Mc & 20-28 Mc)	OEMsr-1045
989	Study of ?AN/APT-4 transmitter	OEMsr-1045
990	Searchlight receiver	OEMsr-1045
991	Modification of receiver to eliminate pulse interference	OEMsr-1045
992	Antenna for Pimpernel	OEMsr-1045
993	Screening of aircraft	OEMsr-1045
994	Investigation aircraft	OEMsr-1045
995	Modification of British ground Cigar for spot jamming	OEMsr-1045
996	Tests of British Carpet II	OEMsr-1045
997a	Carpet spot jamming	OEMsr-1045
997b	Modification of AN/APT-2	OEMsr-1045
998a	Enemy radar frequency and characteristics	OEMsr-1045
998b	Operational testing of APR-2	OEMsr-1045
998c	Enemy utilization of radar	OEMsr-1045
998d	Location of enemy radar sites	OEMsr-1045
998e	Efficacy of RCM equipment	OEMsr-1045
998f	Investigation of enemy communications	OEMsr-1045
999a	Recording for airborne VHF interception work	OEMsr-1045

PROJECTS ASSIGNED TO DIVISION 15 CONTRACTORS

The projects assigned by Division 15 to each of its contractors are given in the following list by RP numbers. The title of each RP number may be found in the pages immediately preceding.

NDCrs-100

RP-399
RP-404

OEMsr-63

RP-381

OEMsr-411

RP-100
RP-103
RP-106
RP-107
RP-110
RP-112
RP-126
RP-135
RP-138
RP-139
RP-141
RP-144
RP-145
RP-146
RP-147
RP-161
RP-162
RP-163
RP-164
RP-165
RP-166
RP-167
RP-168
RP-169
RP-170
RP-171
RP-172
RP-173
RP-174
RP-175
RP-176
RP-177
RP-178
RP-179
RP-180
RP-181
RP-182
RP-183
RP-186
RP-187
RP-188
RP-191
RP-193
RP-202
RP-203
RP-204
RP-205

OEMsr-411 (*Contd.*)

RP-206
RP-207
RP-208
RP-209
RP-210
RP-212
RP-213
RP-214
RP-215
RP-216
RP-217
RP-218
RP-221
RP-222
RP-223
RP-224
RP-225
RP-226
RP-237
RP-242
RP-245
RP-246
RP-250
RP-251
RP-253
RP-257
RP-258b
RP-262
RP-266
RP-267
RP-271
RP-273
RP-275
RP-276
RP-277
RP-279
RP-281
RP-284
RP-285
RP-286
RP-287
RP-288
RP-289
RP-290
RP-291
RP-292
RP-293
RP-294
RP-295
RP-297
RP-298
RP-299
RP-301

OEMsr-411 (*Contd.*)

RP-302
RP-303
RP-304
RP-305
RP-306
RP-309
RP-313
RP-314
RP-315
RP-316
RP-317
RP-318
RP-321
RP-323
RP-324
RP-327
RP-328
RP-329
RP-333
RP-335
RP-336
RP-338
RP-339
RP-340
RP-341
RP-342
RP-343
RP-344
RP-346
RP-348
RP-349
RP-350
RP-354
RP-355
RP-357
RP-364
RP-366
RP-367
RP-368
RP-369
RP-370
RP-371
RP-372
RP-373
RP-374
RP-375
RP-376
RP-377
RP-378
RP-379
RP-380
RP-385
RP-391

OEMsr-411 (*Contd.*)

RP-398
RP-400
RP-401
RP-403
RP-405
RP-406
RP-407
RP-408
RP-409
RP-411
RP-412
RP-413
RP-414
RP-415
RP-416
RP-417
RP-424
RP-425a
RP-426
RP-428
RP-429
RP-435
RP-436
RP-438
RP-442
RP-443
RP-446
RP-447
RP-448
RP-449
RP-452
RP-453
RP-454
RP-455
RP-456
RP-457
RP-458
RP-459
RP-461
RP-462
RP-468
RP-469
RP-470
RP-471
RP-472
RP-474
RP-475
RP-476
RP-477
RP-478
RP-479
RP-480
RP-481

OEMsr-653
RP-136

OEMsr-747
RP-351
RP-353

OEMsr-759
RP-137
RP-269
RP-427

OEMsr-867
RP-136
RP-140
RP-184
RP-185
RP-239
RP-240
RP-241
RP-261
RP-264
RP-310
RP-312
RP-319
RP-320
RP-336
RP-331
RP-406g

OEMsr-895
RP-123
RP-131
RP-198
RP-227
RP-228
RP-229
RP-230
RP-231
RP-252
RP-260
RP-263
RP-268
RP-325
RP-345
RP-352
RP-420b
RP-460

OEMsr-923
RP-160
RP-195
RP-245
RP-270

OEMsr-931
RP-116
RP-156

OEMsr-931 (*Contd.*)
RP-157
RP-158f
RP-243
RP-244a
RP-258a
RP-347
RP-392
RP-394
RP-430a
RP-433
RP-434

OEMsr-936
RP-159
RP-437

OEMsr-937
RP-124
RP-194

OEMsr-940
RP-132
RP-150
RP-152
RP-153
RP-154
RP-155
RP-199
RP-232
RP-234
RP-235
RP-272a
RP-326
RP-356b

OEMsr-966
RP-109
RP-115
RP-132
RP-148
RP-149
RP-150
RP-151
RP-233
RP-249
RP-259
RP-268
RP-272b
RP-326
RP-358
RP-422
RP-440
RP-441

OEMsr-993
RP-122
RP-150
RP-358

OEMsr-1005
RP-192
RP-463
RP-464
RP-465
RP-466
RP-467

OEMsr-1019
RP-158a
RP-434

OEMsr-1024
RP-109a
RP-189
RP-397
RP-450
RP-451

OEMsr-1034
RP-247

OEMsr-1043
RP-158d
RP-244b

OEMsr-1045
RP-999
RP-998
RP-997
RP-996
RP-995
RP-994
RP-993
RP-992
RP-991
RP-990
RP-989
RP-988
RP-987
RP-986
RP-985
RP-984
RP-983
RP-982
RP-981
RP-980
RP-979
RP-977
RP-976
RP-975
RP-974

OEMsr-1060
RP-196

OEMsr-1107
RP-197

OEMsr-1138
RP-307

OEMsr-1176
RP-311

OEMsr-1222
RP-332
RP-439

OEMsr-1275
RP-200

OEMsr-1305
RP-117a
RP-117b
RP-117c
RP-117d
RP-334
RP-359
RP-360
RP-361
RP-362
RP-363
RP-382
RP-383
RP-384
RP-386
RP-388
RP-389
RP-395
RP-402
RP-419
RP-420a
RP-421
RP-425b
RP-431
RP-432
RP-473

OEMsr-1309, OEMsr-1310
RP-356
RP-356a
RP-356c

OEMsr-1357
RP-1586

OEMsr-1430
RP-158c

OEMsr-1456
RP-158e
RP-430b

OEMsr-1458
RP-444
RP-445

SECRET

INDEX

The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed in the reverse of the half-title page.

A-131 tunable magnetron, 40, 43, 425
A-132 multianode magnetron, 44-45
A-133 multianode magnetron, 44-45
ABL (American British Laboratory), radio countermeasures, 287-299, 457
A-f (audio frequency) noise generators, 451-452
  Gaston, 22, 175
  magnetic, 22
AI radar (aircraft interception), countermeasures to, 11-12, 140, 461
AIL
  see Airborne Instruments Laboratory
Air Broadloom (jammer for radar), 386
Air Cigar (British jamming system), 299-300
Air Mark VI (Japanese) radar, 334-335
Airborne antennas, 60-65
  broad-band system, 442
  directivity patterns, 55, 433, 441
  directly-fed wing antennas, 65
  faired-in antennas, 65
  formula for power limit, 443
  frequency range, 55
  lobe-switching antenna, 439-440
  mounting, 57
  sleeve-type, 65, 435-436, 443, 445
  studies on models, 141-143
  summary of types, 60-63
  trailing-wire antennas, 64-65, 443
  V-antennas, 64
Airborne Instruments Laboratory
  antennas and power transmission for nonradar countermeasures, 54-65
  jamming and antijamming techniques, 188-200
  jamming transmitters, 160-187
  magnetic tape recorders, 159
  radio countermeasures, test methods and equipment, 66-75
  receiving and direction-finding techniques, 149-159
  theoretical studies of jamming, 80-146
Airborne jammers, 222-225
  advantages, 128, 215
  AN/APQ-20 (XA-2), 228
  AN/ARQ-8; 174, 183, 222-225
  AN/ARQ-11; 183-184
  Carpet, 275-282, 289-292, 361-363, 385-387
  communication ferret C-1; 150-151, 456
  CXCE, 384
  Dina, 384
  disadvantages, 11
  effectiveness against radar, 222
  Jostle IV, 456
  Mandrel, 267, 383-384
  1.5-kw, 392
  Pimpernel, 389
  preset frequency, 169
  Rug, 384-385, 457
Aircraft-interception radar, countermeasures to, 11-12, 140, 461
AJ techniques
  see Antijamming techniques
Alignment systems for jammers, 397
  double-peaking amplifier-alignment unit, 76
  quado, 178-179, 394
  recommendations for future research, 179
  Stopwatch, 179, 394
Altimeters, radio
  AN/ARN-1; 196-197
  f-m, 413
  German, 140, 196-197, 454-455
  vulnerability to jamming, 140, 196-197, 413
Aluminum foil, use in Chaff, 231, 235, 409
AM-33 amplifier, jamming effectiveness, 383
AM-66/AR-XR power amplifier, use for jamming, 176, 382-383
AM-80/ARA-13 airborne amplifier, 177
AM-96/ARA-13 airborne amplifier, 177
A-m communication, vulnerability to jamming, 193, 395, 397
A-m jamming
  see Amplitude-modulated jamming
A-m receivers, high-frequency, 193
American British Laboratory, radio countermeasures, 287-299, 457
Amplifier back-biasing circuit for antijamming, 252
Amplifier-alignment unit, double-peaking, 76
Amplifiers for jamming systems
  AM-33; 383
  AM-66/AR-XR, 176, 382-383
  AM-80/ARA-13; 177
  AM-96/ARA-13; 177
  AN/ARA-13; 177
  double-peaking alignment unit, 76
Amplitude-modulated communication, vulnerability to jamming, 193, 395, 397
Amplitude-modulated jamming
  by noise, 81-84
  Dina, 162, 170
  effectiveness, 429-432
  noncoherent pulses, 171
  simultaneous f-m and a-m, 81-84, 109
  spark sets, 171-172
  transmitter design, 170-172
  vulnerability of communications receivers, 193
AN-148A antenna, 440
AN/APA-11 pulse analyzer, 417
AN/APA-17 direction finder, 288, 457
AN/APA-27 automatic jammer, 226-228, 388-389
AN/APA-42T1 DF antenna trainer, 422
AN/APG-1 gun-laying radar, antijamming characteristics, 404
AN/APG-1 gun-laying radar, susceptibility to jamming, 257, 404
AN/APG-4 bombsight, vulnerability to jamming, 197
AN/APN-1 altimeter, vulnerability to jamming, 196-197
AN/APQ-5B blind bombing attachment, jamming susceptibility, 404
AN/APQ-9
  see Carpet (jamming transmitter)
AN/APQ-20 airborne jammer for radar, 228
AN/APR-5 radar search receiver, 373
AN/APS-4 radar, jamming susceptibility, 257, 404, 461
AN/APS-19 radar, antijamming modifications, 251
AN/APT-1 jammer, 384
  design considerations, 170, 218
  jamming effectiveness, 167, 430
  noise clipping, 85, 88
AN/APT-2
  see Carpet (jamming transmitter)
AN/APT-4 jammer for radar, 386
AN/APT-5
  see Carpet (jamming transmitter)
AN/APT-10 magnetron transmitter, 387-388
AN/ARA-13 airborne amplifier, 177
AN/ARC-4 receiver, vulnerability to jamming, 193
AN/ARN-1 altimeter, vulnerability to jamming, 196-197
AN/ARQ-2 Jackal jammer, 395
AN/ARQ-8 airborne jamming system, 222-225
  applications, 183
  Dina transmitter, 174
AN/ARQ-10 spot jammer, 176-177
AN/ARQ-11 airborne jamming system, 183-184
AN/ARQ-12 airborne magnetic tape recorder, 156-158, 380

AN/ART-2 pulse jammer, 381-382
modulation, 174
requirements, 174
use against walkie-talkies, 382
AN/ART-3 high-power Jackal jammer, 383, 456
Angels (corner reflector), 241-243
construction, 230-231, 242-243, 412
echoes from, 411
effects of diffraction, 116-117
folding reflector, 412
reflection patterns, 411
required characteristics, 241
AN/GRQ-1 ground-based jammer
antenna system, 64
installation, 180-181
modifications to commercial equipment, 180
use against guided missiles, 393
AN/SRQ-1 ship-borne jammer, 186-187, 392
AN/SRQ-2 magnetic tape recorder, 156-158, 381
AN/SRQ-11 ship-borne jamming system, 183, 185
AN/SRW-2 receiver, jamming vulnerability, 195, 402-403
Antenna selection switch, 435, 445
Antenna trainer, direction-finding, 422
Antennas, 54-65, 433-445
broad-band, 442
coaxial dipole, 445
cone, 434, 439
continuously-rotating, 440
cylindrical, 439, 445
end-fed balanced, 437-438
fan dipoles, 445
fishhook, 296-297, 436
horn-type, 436
lobe-switching, 439-440
long-wire, 443
loop antennas, 440
S-band, 441
sleeve, 65, 436, 443, 445
slot, 436-437, 444
spinners, 377-378
split can, 436, 439
stingaree, 445
stub, 433, 435, 443
TDY, 342
trailing-wire, 64-65, 443
u-h-f, 444
V-antenna, 64
wave, 64, 443-444
waveguide, 434
whip, 440-441
wing, 65
Antennas, design, 54-58
antenna array, 55-56
bandwidth, 54-55
effect of diameter, 55
effect of mounting at an angle, 57
for direction finders, 455-456
installation, 57
optimum height of jamming antenna, 440
polarization, 56
transmission lines and accessories, 58, 63
use of reflectors and wave guides, 55-56
Antennas, radiation patterns, 440-444
cone antennas, 441
continuous antenna patterns, 441
dipole on AT-11 aircraft, 441
effects of antenna coupling, 443-444
loop antennas, 443-444
measurement, 141, 433, 439
search antennas, 438, 440
ship-borne, 55-56, 443
sleeve antennas, 443
slot antennas, 442
steel antenna, 443
stingaree antenna, 445
stub antennas, 441
tank antennas, 433
whip antennas, 441
Antennas, scaled models
airborne antennas, 141-143
ground-based antennas, 143
loop antennas, 375
measurement of radiation patterns, 141
methods for measuring antenna impedances, 143
shipboard antennas, 143
Antennas, theoretical studies, 123-127
cylindrical antennas, 123-124
equivalent point antenna, 124-125
general problems, 123-125
loop antennas, 125-126
search antennas, 126-127
Antijamming techniques, 188-190, 250-254, 259-263, 405-406
alternate operating frequencies, 14
anti-window devices, 253-254
back-biased i-f amplifier, 252
basic principles, 188-189
clipper stages in pulse f-m systems, 191
committee on antijamming, 250-251
filters, 252, 259-260, 405
f-m adapter for radio receivers, 190, 398
frequency coverage, 189
gain control, 252
jamming cancellation systems, 253-254
L-901 video unit, 259
listening-through systems, 173, 177-178
lobe-switched radar, 253
oscillator detuning attachment, 253, 259
pass circuit in pulse receivers, 191, 398
peak clipping of audio voltages, 401
personnel training, 14, 189, 261-262, 421-422
radio-printing attachment, 198-200
recommendations, 262-263
remote-tuning transmitter attachment, 260
test equipment for jamming vulnerability, 66-68
use of audio limiter, 190
use of high directivity, 14
video amplifiers, 406
Anti-window device, 117-122, 253-254
effectiveness, 118-121
reduction in pulse length, 117-118
requirements, 121-122
AN/TPL-1 searchlight-pointing radar, jamming susceptibility, 257, 404
AN/TRC-1 field teletype equipment, jamming vulnerability, 194, 401
AN/TRC-5 pulse communication system, jamming vulnerability, 194-195, 399
AN/TRC-8 transmitter-receiver, electrical characteristics, 402
AN/TRR-2 mine detonator, jamming vulnerability, 195, 402
AN/UPT-1 practice jamming set, 261-262
AN/UPT-T4 practice jamming set, 261-262, 420
Aperiodic meter, detection of radar signals, 95
APQ-2 jammer for radar, 384-385
advantages, 384
modifications for spot jamming, 457
APT-1 transmitter
see Dina jammer (direct-noise amplification)
APT-3 transmitter, 267, 383
ARB aircraft receiver, jamming vulnerability, 402
ARC-1 receiver, performance characteristics, 398
ARQ-8 transmitter
see Dina jammer (direct-noise amplification)
AS-44/APR-5 cone antenna, 434
AS-69 fishhook antenna, 296-297
AS-97/ART whip antenna, 440
AS-161/ART whip antenna, 440
AS-181/APT sleeve antenna, 435-436
AS-222/APA-17 antenna spinner system, 377-378

SECRET

ASB radar, antijamming modifications, 260, 405-407
ASG radar, antijamming characteristics, 403
ASV radar, susceptibility to jamming, 257
ATR transmitter, conversion to barrage jammer, 382
Audio detection of radar signals
  advantages, 431-432
  pulse length, 95
  sensitivity, 95
  signal-to-noise ratio perceived in earphone, 94
Audio limiter for communications antijamming, 190
Audio noise generators
  Gaston, 22, 175
  magnetic, 22
  Tungar bulbs, 452
Audio oscillator, use with pulse analyzer, 414
Audio spectrum analyzers, 30-31
Audio waveform for communications jamming modulation, 162
Autodyne receivers for spot jamming, 288
Automatic jammers, 220-221
  Automat, 226-228, 388-389
  Beagle, 182
  Broom, 181-182, 393
  Carpet II, 290, 300, 387
  Pimpernel, 226, 389
  summary of types, 224-225
  theory of automatic tuning, 397
Automatic search receivers, 205, 374

BA-348-R receiver, vulnerability to jamming, 193
Bagful (recording receiver), 278-279, 287, 299
Bagpipes (communication jamming modulation), 165
Balancing transformer, wide-band, 134
Ballantine Laboratories
  Gaston noise generator, 22, 175
  noise jamming sources, 19-38
Bandwidth adjustment indicator, 417
Barrage jammers, 168-169, 174-176, 216-217, 381-383
  Carpet, 275, 345-346
  comparison with spot jammers, 168, 216
  converted communications transmitters, 172, 175, 382
  definition of barrage jamming, 216
  disadvantages, 345–346
  effectiveness for 27-42 mc communications, 383
  evaluation, 168, 276
  expendable jammer (Chick), 174-175
  15-kw ground jammer (Cigar), 140, 175-176, 389, 400
  f-m jammers, 382, 396
  frequency setting, 76, 168, 219–220
  Jackal, 383, 395, 456, 458
  Jostle IV, 456
  Mandrel, 267, 384
  noncoherent pulse jammer (Pad), 174, 381-382
  operation, 168
  requirements, 107-108
  tests with r-f noise, 394
  transmitter design, 216
  type of modulation, 168, 216
  spark sets, 171-172, 382
Bazooka transformer, frequency characteristics, 433
BC-312-N receiver, jamming vulnerability, 193, 401-402
BC-342-N receiver, jamming vulnerability, 193, 401
BC-348-R receiver, jamming vulnerability, 401-402
BC-603-D receiver
  f-m adapter, 398
  jamming vulnerability, 193-194, 400
BC-624-A receiver, jamming vulnerability, 400-401
BC-624-AM receiver, jamming vulnerability, 193
BC-625-A receiver, jamming vulnerability, 401
BC-639-A search receiver
  jamming vulnerability, 193, 401
  modifications to reduce pulse interference, 371
BC-652-A receiver, jamming vulnerability, 193, 401-402
BC-654-A receiver, jamming vulnerability, 193, 401
BC-659-A receiver, jamming vulnerability, 400-402
BC-669-C receiver, jamming vulnerability, 193, 401-402
BC-699-C receiver, jamming vulnerability, 401
BC-1000-A receiver, jamming vulnerability, 401
BC-1255A frequency meter, 417
BC-1375 antijamming video filter, 259, 405
Beagle (automatic search jammer), 182
Beaver III (ground-based radar jammer), 284
Beechnut (ideograph transmission system), 198, 399
Bell Telephone Laboratories
  communications ferret, 150-151
  Gaston noise generator, 22, 175
  jamming modulations, 81
  jamming transmitters, 160-187
  local oscillator tubes, 40-41
  noise jamming sources, 19-38
  nonradar receiving and direction-finding techniques, 149-159
  photomultiplier tube, 19-20
  "propagation curves," 127
  theoretical studies of jamming, 80-146
  vacuum tube development, 39-53
Beverage wave antenna, 64
Big Ben (German V-2 rocket), 300
Birdnesting (phenomenon of dipoles), 231
Blanket (direction-finding deception), 152-153, 412
  antenna, 153
  crystal-controlled oscillators, 153
Blind bombing, jamming susceptibility, 404
Blinker (search receiver), 287-288
Bomber navigational aids
  countermeasures to, 151, 413
  types, 264
Bombsights, vulnerability to jamming, 197
Boozer (radar warning receiver), 206, 287, 299
British research
  Air Cigar, 299-300
  American British Laboratory, 287-299, 457
  Bagful (recording receiver), 278-279, 287, 299
  Beechnut (ideograph transmission system), 198, 399
  Big Ben, 300
  Boozer (radar warning receiver), 206, 287, 299
  Carpet II, 300
  Chaff, 230-231, 234-237
  Mandrel, 267
  Moonshine, 245, 266-267
  Perfectos (homing system), 295, 380
  Ping Pong (direction finder), 278, 304
  Tinsel (jamming modulation method), 172
  Tuba, 140, 300-302, 390-391
  Window, 234-237
Broad-band antenna system, 442
Broadloom (jamming transmitter), 386
Broom (automatic search jammer), 181-182, 393
BTL
  see Bell Telephone Laboratories
Butterfly circuits for oscillators, 428

C-1 communications ferret, 150-151, 456
C-1906 azimuth homing system for direction finders, 376

Cable, coaxial
see Coaxial cable
Cable, low-reflectivity, 140-141
Calorimetric wattmeter, high-frequency, 418-419
coaxial line sections, 75
microwave wattmeter, 419
water-load type, 419
CAOS-50 AEY filter (antijamming video filter), 405
Carbon granules as noise source, 27
Carpet (jamming transmitter), 275-284, 289-292, 385-387
automatic searching, 290, 387
barrage jamming, 275, 345-346
discriminator circuit, 300
history of operational use, 279-284, 290
limitations, 276-277
modifications permitting 335- to 415-mc operation, 389
performance as spot jammer, 275, 280, 385, 457
use as radar operator training aid, 79
Carpet checker, 418
Carpet output indicator, 418
Carpet tester, 414
Cathode-ray tubes with long afterglow, 407
CBS (Columbia Broadcasting System)
pulse generator, 415
radar jamming transmitters, 214-229
radar receiving and direction-finding equipment, 203-213
radio countermeasures, test methods and equipment, 66-75
Chaff (confusion reflector), 231-237, 408-410
aluminum foil, 231, 235, 409
birdnesting, 231
cutting machine, 231-233
design considerations, 111
determination of induced current, 111-113
dispensers, 410
effectiveness, 273-275, 409, 431
frequency range, 233
number and length of dipoles, 233-234
production methods, 409
response, 113, 409-410
special Chaff bombs, 283
specifications, 231, 408, 410
types, 232-233
unit of Chaff, definition, 233-234
Chaff, flat, 230-231, 234-237
comparison with bent Chaff, 234-236
effect of humidity, 236
frequency range, 234-236
German type, 236-237
length, 236
Chick (expendable jammer), 174-175, 215-216, 391-392
evaluation, 140
parachute-borne, 140, 172
performance, 175
spark type, 392
Cigar (communications jammer)
effectiveness, 140, 400
modifications for spot jamming, 389
type of oscillation, 175-176
Cinaudagraph Corporation, miniature gas triodes, 23-24
Circuits, electronic
amplifier back-biasing circuit for antijamming, 252
butterfly circuit for u-h-f oscillators, 428
pass circuit for pulse receivers, 191
Silent Knight, 373
Clipping, effect on noise spectra, 84-88
advantages, 85-87
definition of clipping, 84
dependence upon bandwidth, 255
Dina noise, 85, 88
effectiveness for jamming, 88, 431
gas tubes, 102, 450
noise-modulated carrier, 88
random noise, 164
rectifiers, 102
spectral distribution, 81, 84-87, 102
CLU-24314 antenna selection switch, 445
Coastal-watch radar, jamming susceptibility, 13
Coaxial cable, 445-447
antenna, 445
bandwidths of resonant-line sections, 446
cavity oscillator, 425-426, 428
effect of copper losses, 446
Federal B-45; 446
filters, 453
impedance of shielded balanced line, 446
line oscillator, 428
mode separation in coaxial oscillator, 446
RG-21/AU cable, 446
velocity of propagation, 132
wide-band coaxial lines, 446
Code systems, 197-200
antijamming printing attachment, 198-200
Beechnut, 198, 399
teleprinters, 197
Voflag, 198, 399
Cold-cathode tubes for noise jamming, 29, 451
Columbia Broadcasting System
pulse generator, 415
radar jamming transmitters, 214-229
radar receiving and direction-finding equipment, 203-213
radio countermeasures, test methods and equipment, 66-75
Communications ferrets, 149-151
C-1 ferret, 150-151, 456
installation, 458
recommendations, 150
requirements, 149-150
Communications jammers, 169-179, 381-383
Chick, 172, 174-175, 215-216, 391-392
Cigar, 140, 175-176, 389, 400
comparison with radar jammers, 215
design considerations, 215
Dina, 85-88, 222-225, 381-382
effectiveness, 165-167, 401
ferrets, 149-151, 456, 458
general jamming problem, 160-162
394
interference generator, 381
Jackal jammer, 383, 395, 456, 458
Jostle IV; 456
monitoring and tracking victim signal, 394
Pad, 174, 381-382
spark jammers, 171-172, 382, 392
Communications search receivers, 371
Communications systems, antijamming characteristics, 188-191, 398-401
Beechnut, 399
comparison of systems, 190
facsimile transmission system, 398-399
f-m receivers, 397-398, 400-402
personnel training, 189
protected communication system, 400
pulse communications, 191, 398
radio-printing systems, 197-200, 399
telegraphy, 190, 197, 399-400
Communications systems, jamming vulnerability, 191-195
a-m receivers, 193, 395, 397
facsimile and teletype systems, 194, 401
f-m receivers, 193-194, 395, 396
pulse systems, 194-195
recommendations, 195
telegraph systems, 393, 395, 397
to c-w and a-m signals, 193
233 A airborne transceiver, 401
Cone antennas
AS-44/APR-5; 434
bandwidth, 439
double-cone assembly, 434
radiation patterns, 441
Confuser, mechanical (noise generator), 26-27
Confusion devices
see Deception and confusion devices
Constriction oscillators as noise jamming source, 25, 451

Continuous wave for jamming, effectiveness, 164-165, 193, 400
Continuous wave magnetrons
A-131; 425
1-kw, 425
self-regulating field excitation, 429
tantalum cylinder cathodes, 425
Continuous wave modulation, 164-165, 193, 400
Controlled-device jammers, 380-381, 392-393
Corner reflectors (radar deception device), 241-244
aircraft-towed, 243
Angels, 116-117, 230-231, 241-243, 411-412
balloon-supported, 242-243
effective echoing area, 241
effects of diffraction, 116-117
for protection from flak, 459
ground-based, 244
naval Spoofs, 459-460
raft-or-boat-supported, 243
types, 241
Corny (tuning of multianode magnetrons), 47
Crystal mixers for spectrum analyzers, 72, 416
Crystal rectifier voltmeter, 420
Crystals for noise jamming source, 28
Curtain (homing device), 295, 379-380
CV-9/APT transmitter output indicator, 418
CV172 diode as noise source, 29
C-w jamming, effectiveness, 164-165, 193, 195, 400
C-w magnetrons
A-131; 40, 43, 425
1-kw, 424, 425
self-regulating field excitation, 429
tantalum cylinder cathodes, 425
C-w modulation, 164-165, 193, 400
C-w oscillators, 425-426
GE-L-3 triode, 426
GE ZP-449 triode, 426
microwave, 426
ZP-522 triode, 428
C-w telegraphy, jamming of, 396
CXCE (radar jammer), 384
Cylindrical antennas
impedance characteristics, 439, 445
theoretical study, 123
Cylindrical magnetrons, 429

D-1905 spurious response indicator, radar, 372
D-9000 search receiver, 208-213
D 159076 photomultiplier tube, 20
DBA direction finder, 379
DBM direction finder, 378-379
Deception and confusion devices, 408-413
Angel, 116-117, 241-243, 411-412
blanket masking signal system, 152-153, 412
Chaff, 111-113, 231-237, 273-275, 408-410
corner reflectors, 116-117, 241-244, 411-412, 459
direction-finding deception systems, 412
Elmer, 309, 413
Fishline, 238
mechanical, 26-27
Moonshine, 245, 266-267
Peter, 245-247, 306, 412-413
pulse transmitters, 247-248
Rope, 113-115, 237-240, 363-365, 410
Stardust pulse repeater, 412
summary of development work, 423-424
Turnstile, 230-231, 238-239
use of enemy frequency, 247-248
Deflection modulation, effect on screen brightness, 98-99
DF (direction finders)
see Direction finders
Differential analyzer, study of electron paths, 144-145
Dina Chick (expendable jammer), 172, 174-175, 215-216, 391-392
evaluation, 140
performance, 175
spark type, 392
Dina jammer (direct-noise amplification), 381-382, 384
design considerations, 170, 218
jamming effectiveness, 167, 430-431
noise clipping, 85, 88
use against guided missiles, 381
use against SLC radar, 361-362
Diode as noise source, 29
Dipoles
see Antennas; Direction finders; Window
Direct-detection search receivers, 208
Direction finders, 11, 375-380
see also Antennas; Homing devices and attachments
against radar, 207, 210-212
airborne, 300-1000 mc, 377
AN/APA-17; 288, 457
antenna spinner system, 377-378
antennas, 375, 422, 440, 455-456
comparison with homing system, 206-213
countermeasures to, 151-153, 412, 413
DBA, 379
DBM, 378-379
Judy, 380
NLS-694; 151
Ping Pong, 278, 304
setter (attachment for frequency range), 375-376
ship-borne, 300-1000 mc, 378
spinning loop, 380
submarine system, 379
trainers, 79, 422
Directivity patterns of antennas
see Antennas, radiation patterns
Direct-noise amplification (Dina), 381-382, 384
design considerations, 170, 218
jamming effectiveness, 167, 430-431
noise clipping, 85, 88
use against guided missiles, 381
Donutron tubes (internally-tuned), 426-427

E-409 remote-tuning transmitter attachment, 260
E-410 antijamming filter, 260
E-411 gang tuning radar attachment, 260
E-413 remote-tuning transmitter attachment, 260
E-510 high-pass antijamming filter, 259
E-512 oscillator detuning attachment for antijamming, 259
E-515 high-pass antijamming filter, 259
E-1601/1602 detector and video units for antijamming, 259
E-1610 high-pass antijamming filter, 259
Early-warning radar, countermeasures to, 359-360
deception devices, 349-350
jamming, 13, 458
Rope, 359
Early-warning receivers
see Warning receivers
Echoes
from shell bursts, 245
means of distinguishing real from artificial, 406-407, 459-460
radar, 128-129, 143-144, 458
ships, 128-129
860 mc tetrode resnatron, 52
884 gas tube, use as noise source, 22, 449, 450
Electra (German bomber navigational aid), 264
Electron tube development, 39-53
5-kw triode for 70- to 350-mc range, 423-424
flute tubes, 45
L-14 tunable broad-band amplifier, 423
local oscillator, 425

magnetrons, 39-44, 136, 144-145, 422-428
resnatrons, 51-53, 422, 428-429
techniques in tracing electron paths, 423
ultra-high-frequency diode, 422
Elephant (ship-borne jamming system), 228-229, 253-254, 300, 390-391
Elmer (communications deception device), 309, 413
End-fed balanced antennas, 437-438
Enemy radar
see Japanese radar
Enemy research
see German research
EW radar (early-warning), countermeasures to, 359-360
deception devices, 349-350
jamming, 13, 458
Rope, 359
Expendable jammer (Chick), 172, 174-175, 215-216, 391-392
evaluation, 11, 140
performance, 175
spark type, 392

F-2306 Carpet output indicator, 418
Facsimile transmission system
antijamming characteristics, 398-399
vulnerability to jamming, 194
Fan antennas, impedance characteristics, 445
Fanny (homing attachment for direction finders), 376
FD radar (fire-control)
antijamming attachments, 259, 405
range indicator, 406
susceptibility to jamming, 257
Federal B-45 coaxial cable, 446
Federal Telecommunication Laboratories, Inc.
jamming and antijamming techniques, 188-200
jamming transmitters, 160-187
nonradar receiving and direction-finding techniques, 149-159
vacuum-tube development, 39-53
Federal Telephone and Radio Corporation, sealed-off resnatron, 52-53
Ferrets for searching and monitoring communications systems
C-1 ferret, 150-151, 456
installation, 458
recommendations, 150
requirements, 149-151
FG101 German radio altimeter, 140
FG178A thyratron, noise output, 449
15-kw ground jammer (Cigar)
effectiveness, 140, 400
modifications for spot jamming, 389
type of oscillation, 175-176
Fighter planes, countermeasures to, 293-295
Beaver III; 284
communications interference, 271-273
Curtain, 295
Perfectos, 295
radar interference, 272
radar screens, 294-295
Filters, 134-135
band-pass, 453
coaxial filters, 135, 453
general properties, 135
microwave, 453
75-mc low-pass filter, 452
u-h-f, 452, 453
Filters for antijamming
E-410; 260
E-510; 259
E-515; 259
E-1610; 259
high-pass filter, 405
RC filter, 252
RLC filter, 252
video filter, 405
Fire-control radar
Mark IV; 257, 259, 405, 406
Mark 8; 403
SCR-545; 257, 404
Fishhook antenna, 296-297, 436
Fishline (radar deception device), 238
5J21 (ZP-612) magnetron
cathode, 48
characteristics, 44
response to noise modulation, 427-428
tuning method, 48
wave-guide transformer, 46, 49
5J29 (ZP-579) magnetron
characteristics, 40, 43
design and performance, 422
efficiency, 423
5J30 (ZP-590) magnetron
characteristics, 40
electron escape, 42
frequency range, 43, 45
5J31 (ZP-584) magnetron, 40, 43
5J32 (ZP-646) magnetron
characteristics, 40, 43
electron escape, 42
5J33 (ZP-676) magnetron, 40, 43, 45
Flak, radar-controlled, countermeasures to, 269-271, 279-284, 289-293
aircraft flying formation, 270
Carpet, 279-282, 289-292
Chaff, 282-284, 292-293
corner reflectors, 459
evasive action, 270
Flute tubes, 45
F-m adapter, use in receivers, 190, 398
F-m altimeters, vulnerability to jamming, 196-197, 413
F-m communications systems
antijamming characteristics, 397, 400-402
crystal-controlled, 395
vulnerability to c-w jamming, 193-194, 400
vulnerability to f-m barrage jamming, 396
F-m jamming
see Frequency-modulated jamming
F-m oscillators for panoramic reception, 371
Formulas
current distribution induced in Chaff, 111-113
energy density of pulsed signals, 84
modulation index, 81
noise current at cathode photocell, 19
output spectrum for a-m by noise, 81
output spectrum for f-m by a sine wave, 81
output spectrum for f-m by noise, 81
output spectrum for simultaneous f-m and a-m, 82-84
output spectrum for simultaneous f-m by noise and sine wave, 82
plasma-ion oscillation for gas-discharge tubes, 21
radial motion of the electron in magnetrons, 136
rate of ion production in gas tubes, 101
sawtooth frequency modulation, 106-107
sinusoidal frequency modulation, 105
spectral distribution of clipped noise wave, 84
square-wave frequency modulation, 107
triangular frequency modulation, 107
Frequency meters
accuracy, 204
bandwidth adjustment indicator, 417
BC-1255A, 417
heterodyne frequency meter, 417
methods for pretuning jammers, 418
portable battery-operated, 417
wavemeter, 417-418
Frequency modulator, type P-550; 67
Frequency multiplier, P-554; 68
Frequency-modulated altimeters, jamming vulnerability, 196-197, 413
Frequency-modulated communications systems
antijamming characteristics, 397, 400-402

SECRET

crystal-controlled, 395
vulnerability to c-w jamming, 193-194, 400
vulnerability to f-m barrage jamming, 396
Frequency-modulated jamming, 104-110, 162
applications, 430-432
barrage jamming, 382, 396
by noise, 81-82, 394
effectiveness, 163, 393-394, 396, 429
electromechanical method, 170
electronic method, 169-170
Jackal jammer, 383, 395, 456, 458
jittered f-m, 108-109, 396, 432
pulses, 398
requirements, 107-108
sawtooth, 106-107
simultaneous f-m and a-m, 82-84, 109
sinusoidal, 81-84, 105
spot jamming, 387
square-wave, 107
transmitter design, 169-170
triangular, 107
types, 108
variation of coil inductance, 170
Frequency-modulated oscillators for panoramic reception, 371

Gas tube noise sources for jamming, 21-25, 449-452
2C4 gas triode, 449
2D21; 450
6D4 gas tube, 23-25, 102, 423, 449-451
2050 gas tube, 450
audio noise sources, 21-22
clipping, 102
cold-cathode, 29, 451
FG178A thyratron, 449
hot-cathode, 451
in magnetic fields, 24-25, 101-102
plasma region, 21, 101
rate of ion production, 101
video noise sources, 23-25
Gaston (audio noise generator), 22, 175
GCI radar (ground-controlled interception)
jamming of, 12, 140
warning receiver, 11
GE ZP-449 c-w oscillator, 426
General Electric Company
c-w oscillators, 425-426
differential analyzer, 144-145
limitations of magnetrons, 42-43
neutrode magnetron, 43
noise jamming sources, 19-38
1-kw magnetrons, 44-50
radar deception, 230-248
radio countermeasures, test methods and equipment, 66-75
6D4 noise unit, 24-25
spectrum analyzers, 68-74
TDY radar jamming transmitter, 214
vacuum tube development, 39-53
General Radio Company
radio countermeasures, test methods and equipment, 66-75
sound analyzer, 30
TPQ-T2 signal generator, 261-262, 421
German research
Big Ben (V-2 rocket), 300
bomber navigational aids, 264
control mechanism of BIVb tank, 413
flat Chaff, 236-237
Hs-293 glider bomb, 65, 195-196, 445
radar, 234, 297-299, 457, 460
radio altimeters, 140, 196-197, 454-455
Germanium crystals, use as modulators, 72
GL-522 oscillator, use as a third-harmonic generator, 429
GL radar (gun-laying), countermeasures to, 360-365
Carpet, 275-282, 289-292, 385-387
Chaff, 111-113, 231-237, 273-275, 408-410
effectiveness, 350-352
operational problems, 360-361
requirements, 12
Rope, 113-115, 237, 240, 363-365, 410
GL radar (gun-laying), warning receiver, 11
Glide bombs, countermeasures to
see Guided missiles, countermeasures to
GM jammers
see Guided missiles, countermeasures to
Gold-copper alloy solder, 145, 423
GR (General Radio Company)
radio countermeasures, test methods and equipment, 66-75
sound analyzer, 30-31
TPQ-T2 signal generator, 261-262, 421
Ground forces, use of radio countermeasures, 309-310, 367-368
Ground-based antennas, 58-60
bandwidth, 55
directivity, 55-56
for AN/GRQ-1 jammer, 64
models, 143
use against AI and GCI radar, 55-56
wave antenna, 64
Ground-based jammers, 180-183
advantages, 11
AN/GRQ-1; 64, 180-181, 393
Beagle, 182
Beaver III; 284
Broom, 181-182, 393
Cigar, 140, 175-176, 389, 400
disadvantages, 215
Elephant, 228-229, 253-254, 300, 390-391
Piano, 182-183
Tuba, 140, 300-302, 390-391
Ground-controlled interception radar
jamming of, 12, 140
warning receiver, 11
Guided missiles, countermeasures to, 179-189
airborne jammers, 183-184
AN/GRQ-1 jamming equipment, 64, 180-181, 393
AN/SRQ-1 multi-channel jammer, 186-189, 392
automatic search jammers, 181-182, 393
Dina, 381-382
effect of reflected radar waves, 380
effectiveness, 195-196, 303
MAS ship-borne jammers, 185-186, 392-393
1.5-kw airborne jammer, 392
Peter Pan jamming system, 155-159, 381
Piano, 182-183
ship-borne jammers, 185-187
specifications for jammers, 180
Gun-laying radar, countermeasures to
see GL radar (gun-laying), countermeasures to
Gun-laying radar, warning receiver, 11

H100 video spectrum analyzer, 30
H205 peak reading voltmeter, 31
H206 tube tester, 31
H300 video spectrum checker, 30
H500 audio spectrum analyzer, 30
Hallicrafter S-27D search receiver, 371
Harvard University
see Radio Research Laboratory
Hen (expendable transmitter for propaganda broadcasting), 398
Heterodyne frequency meter, 417
Hewlett-Packard wave analyzer, 31
Hipersil transformer cores, 33
History of operational use, 264-310
air forces, 269-277
British, 264-267, 299-302
civilian aid, 268-269, 277-278, 299-300
European Theatre, 287-299
ground forces, 309-310, 367-368
Mediterranean Theatre, 277-287
naval operations, 302-309
Normandy invasion, 457
Pacific Theatre, 311-368

[redacted]

Homing devices and attachments, 376-377
applications, 207
aural or visual indication, 378
C-1906 azimuth homing system, 376
comparison with direction finders, 206-207, 213
Curtain, 295, 379-380
Fanny, 376
limitations, 207
Moth, 379, 442-443
Perfectos, 295, 380
radar homing bomb, 257, 404
Tail, 376
types used against radar, 206-207, 210, 213
v-h-f, 377
Horn-type antenna, 436
Hs-293 glider bomb
antenna patterns, 65, 445
jamming vulnerability, 195-196

Ideograph transmission system (Beechnut), 198, 399
Ignoramus theory, search receivers, 138-139
Impulse and time code systems
Beechnut, 198, 399
Voflag, 198, 399
Intensity modulation, effect on screen brightness, 98-99
Interference generators, 261-262, 381, 421, 422

Jackal (f-m barrage jammer)
AN/ARQ-2; 395
AN/ART-3; 383, 456
effectiveness, 395
installation in aircraft, 458
Jammers
see also Corner reflectors; Window
airborne, 150-151, 183-184, 222-225, 392
alignment units for, 178-179, 394
amplifiers for, 176-177, 382-383
automatic, 181-182, 220-221, 226-228, 388-389
design requirements, 173
expendable, 172, 174-175, 215-216, 391-392
ground-based, 175-176, 180-183, 284, 389
of communications, 85-88, 149-151, 160-179, 381-383
of controlled devices, 13, 380-381, 392-393
of guided missiles, 155-159, 179-187, 195-196, 380-382
of radar, 172-175, 214-229, 383-392, 457-458
practice sets, 403, 415, 421-422
pulse, 174, 381-382
ship-borne, 185-187, 228-229, 390-393
signal-repeating, 155-159, 182-183
step-tone, 401
summary of types, 11-13
Jammers, design considerations, 169-173, 214-222
amplitude-modulation methods, 170-172
barrage versus spot jamming, 216
communications versus radar jammers, 215
conversion of communications transmitters, 172
enemy equipment, 214-215
expendable, 172
frequency setting, 219-222
frequency-modulation methods, 169-170
listening-through systems, 173
minimum effective distance, 218-219
power requirements, 218-219
sideband energy distribution, 217-218
spot jamming, 216
tactical considerations, 221-222
types, 216-217
Jamming, countermeasures to
see Antijamming techniques
Jamming, theoretical studies, 80-146
effectiveness calculations, 140-141
frequency modulation, 104-110
noise studies, 80-104
transmission and reflection of energy, 110-135
Jamming methods
a-m, 81-84, 170-172, 193, 429-432
audio waveform requirements, 162
barrage jamming, 168-169, 174-176, 216-217, 381-383
c-w modulation, 164-165, 193, 400
f-m, 81-84, 104-110, 393-394, 456-458
noise, 19-38, 80-99, 163-165, 448-452
periodic jamming, 255-256
pulse modulation, 171, 174, 381-382, 398
qualitative comparison of types, 82
random jamming, 255-256
selection of type, 165, 216-218
sine-wave modulation, 165
spot jamming, 168-169, 176-179, 275-276, 384-387
Jamming methods, effectiveness
a-m, 255-256, 430-432
barrage jamming, 168, 276, 383
c-w modulation, 164-165, 193, 195, 400
dependent factors, 161, 395
effect of receiver bandwidth, 256
field tests, 383
f-m, 81-84, 393-394, 396, 429-430
from defensive aspect, 256
from offensive aspect, 255-256
J/S ratio, definition, 255
method of measuring, 140-141, 461
noise, 88, 255-256, 431
periodic jamming, 256
power requirements, 167
pulse modulation, 430, 432
radio waveform requirements, 162-163
spectrum of most effective type, 393-394
speech-masking effectiveness, 393
spot jamming, 168
Jamming sets for training, 420-422
100-350 mc, 421
175-550 mc, 420
450-720 mc, 420-421
450-1000 mc, 422
L-105; 403
Jamming susceptibility
blind bombing, 404
bombsights, 197
communication systems, 191-195, 393-398, 401
German Hs-293 glider bomb, 195-196
Japanese communications equipment, 396-397, 402-403
Loran navigational system, 395
radar, 12-13, 257-258, 403-404, 429-431
radio altimeters, 140, 196-197, 413
radio telegraphy, 393, 395, 397
receivers, 166, 193-195, 400-403
test equipment, 66-68
Jansky and Bailey, jamming and antijamming techniques, 188-200
Japanese communication equipment, jamming susceptibility, 396-397, 402, 403
Japanese direction finders, countermeasures to, 151-152, 413
Japanese radar
airborne, 311, 334-342
allied reconnaissance during World War II; 277-279, 287-289, 317-325, 346-349, 354-359
characteristics, 458
GL and SLC radar, 313
ground radar, 333
Mark I; 333
Mark VI; 334-335
Mark B, 333
ship-based, 312-313
surface radar, 325-334
Jostle IV (barrage jammer), 456
J/S ration (jamming to signal power), 255
Judy (instantaneous direction-finding system), 380

Kites
see Angels (corner reflector)
Klystron, reflex, 68-69, 71
Knickebein (German bomber navigational aid), 264

L-14 parallel-plane triode
application, 41-42
characteristics, 40
design, 423
L-104 multianode magnetron
characteristics, 44
design, 424
tuning method, 47-50
L-105 jamming signal generator, effectiveness, 403
L-901 video unit for antijamming, 259
LC, tuning of multianode magnetrons, 47-48
Listening-through radio jamming, 173, 177-178
Litton Engineering Laboratories, vacuum tube development, 39-53
Lobe-switching antennas, 439-440
Local oscillators, 40-41, 425
Long-wire antennas, 443
Loop antennas
circle, 125-126
equations describing features, 440
radiation patterns, 125-126, 443-444
rhombus, 126
square, 126
techniques of modeling, 375
Loran navigational system, vulnerability to jamming, 395

Magnetic audio noise generators, 22
Magnetic tape recorders, 155-158
AN/ARQ-12; 156-158, 380
AN/SRQ-2; 156-158, 380
use in Peter Pan jamming system, 155-157, 381
vicalloy tape, 157
XN-1; 156-158
Magnetrons, 39-51, 422-428
characteristics, 40
c-w, 40, 43, 425, 429
cylindrical, 429
design of electromagnets, 424
donutron, 426-427
filament regulator, 144, 423
flute tubes, 45
for jamming, 225, 387-388
high-power, 50
limitations, 42-43
medium-power, 42-44
method for "cold" testing, 424
modulation, 427-428
1-kw, 44-50, 424-425
Piccolo, 44, 49-50, 424
scaling formula for new designs, 425
specifications, 44-45
Squirrel-Cage, 39-41, 426-427
summary of development work, 423-424
theoretical studies, 136, 144-145
waveguide output magnetrons, 425
Magnetrons, multianode, 45-50
A-132; 44-45
A-133; 44-45
C- and L-rings, 47-48
cathode, 48-49
characteristics, 44
diode cutout, 50
L-104; 44, 47-50, 424
magnetic field design, 46
output, 46
Piccolo tubes, 49-50
radial-vane type, 46
612 L, 44
suggested improvements, 50
tuning methods, 46-48
use of mumbo, 46-47
ZP-594; 44, 49, 424
ZP-595; 50-51, 422
ZP-597; 44, 49, 424, 427
ZP-612 (5J21); 44, 46-50, 427-428
ZP-615; 44, 49
ZP-616; 44, 48, 49, 424
ZP-639; 44, 49
ZP-693; 44
ZP-838; 44
Magnetrons, neutrode
characteristics, 40, 44
ZP-647; 43-45
ZP-675; 40, 43
ZP-676; 40, 43, 45
ZP-677; 43
ZP-685; 43-45
Magnetrons, split-anode
characteristics, 40, 44, 51
limitations, 42-43
recommendations, 43
types, 43
ZP-579; 40, 43, 422-423
ZP-584; 40, 43
ZP-590; 40, 42-43, 45
ZP-595; 50-51, 422
ZP-599; 44-45
ZP-633; 40, 43, 423
ZP-636; 50-51, 423
ZP-646; 40, 42-43
ZP-666; 40, 43
Magnetrons, tunable
A-131; 40, 43, 425
radar jammers, 387-388
6J21; 425, 428
Mandrel (barrage jammer), 267, 383
Mark I (Japanese) radar, 333
Mark IV radar
antijamming modifications, 259, 405
range indicator, 406
susceptibility to jamming, 257
Mark 4E (Japanese transmitter-receiver), jamming vulnerability, 402
Mark VI (Japanese) radar, 334-335
Mark 8 radar, antijamming characteristics, 403
Mark 31 (radar-controlled missile), jamming vulnerability, 257, 404
Mark B (Japanese) radar, 333
MAS ship-borne jammer, 185-186, 392-393
Masking signal system for radio communication, 412
Massachusetts Institute of Technology, antijamming research and development, 249-260
Mechanical noise generators, 25-28
carbon granules, 27
confuser, 26-27
rotary spark-gap, 28
speed-x buzzer, 28
Meter detection of radar signals
aperiodic meter, 95
evaluation, 431-432
periodic meter, 95
pulse length, 95
sensitivity, 95
Meters, frequency
see Frequency meters
Microwave c-w power oscillators, 426
Microwave filters
design, 453
insertion loss, measuring techniques, 453
Microwave radar, countermeasure to
see Angels (corner reflector)
Microwave search receivers, 288, 420
Microwave wattmeter, 419
Mine detonator, jamming vulnerability, 195, 402
Missiles, self-guided
see Guided missiles, countermeasures to
MIT, antijamming research and development, 249-260
Modulation index
formula, 81
limits, 82, 108
Modulations for jamming
see Jamming methods
Monimax transformer cores, 33, 36-37
Moonshine (pulse-repeating system), 245, 266-267
Moth (self-guided homing missile), 379, 442-443
Multianode magnetrons
see Magnetrons, multianode
Mumbo (tuning of multianode magnetrons), 46-47

Naval Research Laboratory, blanket antenna, 153
Naval Spoofs (seaborne corner reflectors), 459-460
Naval Training School, Fort Lauderdale, Florida, 261

SECRET

Navigational aids for bombers
countermeasures to, 151, 413
types, 264
Neutrode magnetrons
characteristics, 40, 44
ZP-676; 40, 43, 45
Nickel-silicon-iron alloy transformer cores, 33
931 photomultiplier, 19-20
frequency spectrum, 99-101, 448
life tests, 448
noise spectrum, 20
operating characteristics, 448
tube tester, 31
NLS-694 aircraft direction finder, 151
Noise, effect on signal visibility
see Signal visibility through noise
Noise, jamming methods, 80-99
clipped, 84-88, 102, 431, 450
effectiveness, 91-99
modulated, 80-84, 163-165, 255-256
rectified, 88-93, 450
Noise analyzer, 420
Noise generators
see also Gas tube noise sources for jamming
audio, 21-22, 175, 451-452
for static burst jamming, 397
magnetic, 22
mechanical, 25-28
P-551; 67
video, 23-25, 451
voice-frequency, 451
Noise modulations for jamming, 80-84
advantages, 163-164, 217
a-m by noise, 81-84
clipped noise, 164, 255-256
disadvantages, 164
effectiveness, 88, 255-256, 431
f-m by noise, 81-82, 394
of communications, 163-165, 398
random noise, 163-165
thermal noise, 163-164
Noise sources for jamming, 19-38, 448-452
constriction oscillator, 25, 451
gas tubes, 21-25, 101-102, 449-452
moving arc, 29
noise generators, 25-28, 451
photoelectric noise, 19-21, 99-101, 448, 452
semiconductors and crystals, 28
specifications for satisfactory sources, 19
summary of development work, 423-424
transformers, 32-38, 102-104
Tungar bulbs, 452
Noise spectra, effect of clipping
see Clipping, effect on noise spectra
Noise transformers, video, 32-38
core losses, 34
core materials, 33
design, 36-38, 454
impedance measurements, 33
tests, 37-38
Noise tube tester, 31, 419-420
Noise-measuring techniques, 29-32
audio spectrum analyzers, 30-31
equalization of noise, 31-32
theoretical analysis of noise, 29-30
tube testers, 31, 419-420
video spectrum analyzers, 30, 416
Noise-measuring voltmeter, 31, 451
Noise-modulated carrier, effect of clipping, 88
Noise-modulated jammer (Mandrel), 267, 383-384
NRL (Naval Research Laboratory), blanket antenna, 153

OCC spectrum analyzer, 68-70
Officer training, radar antijamming techniques, 261
Ohio State University
antennas and power transmission for nonradar countermeasures, 54-65
radar cross sections of aircraft, 130-131
Oilcan tube, 41
1.5-kw airborne jammer, 392
158J (u-h-f diode), 422
Oscillators
audio, 414
constriction, 451
detuning attachment for antijamming, 253, 259
f-m, 371
local, 40-41, 425
practice jammers, 261-262, 403, 415, 420-422
pulsed, 413-415
r-f sweep generator, 414
self-quenched, 174
test oscillators, 67-68, 413-415
Oscillators, ultra-high-frequency, 425-429
butterfly circuit, 428
coaxial cavity oscillator, 425, 428
coaxial line oscillators, 428
c-w oscillator, 425-426, 428
magnetically-focused velocity-modulation tube, 426
magnetrons, 426-429
radial cavity oscillator, 429
random-pulsed triode cavity oscillator, 428
resnatrons, 428-429
third-harmonic generator, 429

P-519 test oscillator, 67
P-523-A test oscillator, 415
P-525-A oscillator, 415
P-550 frequency modulator, 67
P-551 noise generator, 67
P-552 test oscillator, 67
P-553 test oscillator, 68
P-554 frequency multiplier, 68
Pad (noncoherent-pulse jammer), 381-382
modulation, 174
requirements, 174
self-quenched oscillator, 174
use against walkie-talkies, 382
Panoramic Radio Corporation, nonradar receiving and direction-finding techniques, 149-159
Panoramic search receivers, 153-155
advantages, 204-205
electronic tuning, 153-154, 371
f-m oscillators, 371
Panther, 154-155
37- to 43-mc, 371
Panoramic spectrum analyzer, 415
Panther (panoramic receiver), 154-155
Parachute Chicks, applications, 140, 172
Parallel-plane triodes and tetrodes, 39, 41-42
Pass circuit for pulse receivers, 191
Perfectos (airborne radar system), 295, 380
Periodic jamming
effectiveness against intensity-modulated scopes, 256
types, 255
Periodic meter, detection of radar signals, 95
Permalloy-ribbon transformer cores, 33
Personnel training, 77-79
antijamming techniques, 14
antijamming training set, 261-262, 421
communications operators, 189
courses, 77-78, 261, 316-317
direction-finding trainers, 79, 422
films, 77, 261-262
interference generators, 381, 421-422
jamming signal generators, 261-262, 403, 415, 420-422
Navy SC radar for antijamming training, 422
phonograph records of jamming signals, 422
practice jamming sets, 261-262, 420-421
radar operator training aids, 79
spot-jammer operator, 79, 276
Peter (electrical pulse repeater), 245-247
field tests, 247, 412-413, 457
frequency range, 246

SECRET

modulation procedures, 247
procedures for confusing enemy radar, 245-246
purpose, 306
use of L-14 tube, 41-42
Peter Pan (signal-repeating jammer), 155-159
a-c bias method of recording, 156
accessories, 159
countermeasure for guided missiles, 155
production, 159
recorders, 155-157, 381
Phase-modulated jamming
see Frequency-modulated jamming
Photomultiplier tube, 19-20
frequency spectrum, 99-101, 448
life tests, 448
noise spectrum, 20, 99-101
operating characteristics, 448
recommendations, 21
tube tester, 31
Piano (signal-repeating jammer), 182-183
Piccolo magnetrons
characteristics, 44
multianode, 49
1-kw tunable c-w magnetrons, 424
Pimpernel (automatic jammer), 226, 389
Ping Pong (British direction finder), 278, 304
Plasma region of gas tubes, 21, 101
Porcupines (B-29 with barrage-jamming installation), 362-363
Portable spectrum analyzer, 73-74
Power meter, u-h-f, 418
Practice jamming sets, 420-422
100-350 mc, 421
175-550 mc, 420
450-720 mc, 420-421
450-1000 mc, 422
AN/UPT-1; 261-262
AN/UPT-T4, 261-262, 420
L-105; 403
X-band jammer, 415
Printing systems, radio, 197-200
antijamming attachment, 198-200
antijamming characteristics, 399
impulse and time code systems, 198
teleprinters, 197
Propagation studies, meteorological observations, 146
Proximity fuze, countermeasure to, 13, 159
Pulse analyzers
AN/APA-11; 417
use of audio oscillator, 414
Pulse communications systems, antijamming techniques
clipper stages, 191
pass circuit, 191, 398
tests, 398
Pulse communications systems, identification, 371
Pulse communications systems, jamming susceptibility
AN/TRC-5; 194-195, 399
noise jamming, 398
phase-modulation system, 191, 398
susceptibility to resistance noise, 397
tests, 191
Pulse repeaters (deception devices)
Moonshine, 245, 266-267
Peter, 245-247, 306, 412-413, 457
Stardust, 412
Pulse search receiver, 371
Pulse stretcher for radar search receivers, 373
Pulse transmitters for radar deception, 247-248
Pulsed oscillators, 413, 415
Pulses, efficiency for jamming, 167
advantages, 84
against guided missiles, 195
barrage jamming, 432
f-m pulses, 398
noncoherent pulses, 165, 171
Pad, 174, 381-382
tests, 402

Quado (jamming frequency alignment indicator), 178-179, 394
Quadratic rectifiers, 90

Radar countermeasures, 203-213
Angels, 241-243, 411-412
Chaff, 111-113, 231-237, 273-275, 408-410
effectiveness, 353, 366-367
homing and direction-finding systems, 210-213
Moonshine, 245, 266-267
Peter, 245-247, 412-413, 457
search receivers, 203-205, 208-213, 371-374
table of receiver types, 209-210
warning receivers, 11, 205-206, 213, 413
Radar countermeasures, design considerations, 203-207
analysis of enemy radar, 203-204
analyzing and indicating equipment, 204-205
antennas, 58-63, 433
automatic search receivers, 205, 374
direction-finding systems, 207
homing systems, 206-207
sensitivity of radar search receivers, 205
test equipment, 76-77
warning receivers, 205-206
Radar deception and confusion devices
see Deception and confusion devices
Radar echoes
artificial, 410
from ship targets, 128-129, 458
use of models for experiments, 143-144
Radar homing bomb, jamming susceptibility, 257, 404
Radar jammers, 172-175, 214-229, 383-392, 457-458
AN/ARQ-8; 179, 183, 222-225
Broadloom, 386
Carpet, 275-282, 289-292, 361-363, 385
Chicks, 172, 174-175, 215-216, 391-392
comparison with communications jammers, 215
CXCE, 384
design considerations, 215
Dina, 384
effectiveness, 255-256, 431
Elephant, 228-229, 253-254, 300, 390-391
Mandrel, 267, 383
Pimpernel, 226, 389
Rug, 384-385, 457
table of types, 222-225
Tuba, 140, 300-302, 390-391
tunable magnetron, 387-388
Radar operator training aids, 79
Radar propagation studies, meteorological observations, 146
Radar reception through noise, 93-96
aperiodic meter, 95
aural perception, 94
comparison of methods of presentation, 95-96
linear detection, 94
meter detection of signals, 95, 431-432
periodic meter, 95
quadratic detection, 94
quantitative expressions, 94-95
sensitivity of indicating methods, 94
signal-to-noise ratios, 93-94
visual perception, 93-95, 431-432
Radar reflections, 130-131
Radar screens, 288, 294-295
Radar search receivers, 208-213, 371-374
1000-3100 mc, 372-373
3000-6000 mc, 373-374
AN/APR-5; 373
autosearch airborne receiver, 205, 374
blanking circuit, 373
direct-detection receivers, 208
pulse stretcher for increased sensitivity, 373
recording unit, 374

sensitivity, 205
single signal receiver, 373-374
Spud, 373
tuning units, 208, 372-373
types, 209-210
use in analyzing enemy radar, 203-204
Radar spurious response indicator, 372
Radar system for practice jamming, 429-430
Radar systems, antijamming characteristics, 249-260, 403-408
AN/APG-1 (autotracking gun-laying radar), 404
AN/APQ-5B (blind bombing attachment), 404
AN/APS-4 (search and interception), 404
AN/APS-19 (search and interception), 251
AN/TPL-1 (searchlight-pointing radar), 404
ASB (detection of surface vessels), 260, 405-407
ASG (detection of surface vessels), 403
Mark IV, 259, 405
Mark 8 (fire-control), 403
recommendations, 262-263
SCR-268; 259
SCR-296; 259
SCR-521A, 403
SCR-717B (detection of surface vessels), 259, 403, 406
SCR-720A (night fighters), 404
Radar systems, jamming susceptibility, 257-258, 403-406, 429-431
AI radar, 12, 461
AN/APS-4 radar, 257, 404, 461
ASB, 405-406
ASV, 257
coastal-watch, 13
early-warning, 13
gun-laying, 12, 404
Mark IV, 257
Mark 31; 404
Mark XXXI, 257
RHB (radar homing bomb), 257, 404
SCR-268; 257, 403
SCR-545 (fire-control radar), 257, 404
SCR-720A, 404
searchlight-control, 12
searchlight-pointing radar, 257, 404
type A presentations, 430
type B presentations, 430
Radar video analyzer, 391
Radar warning receivers
see Warning receivers
Radar-controlled flak, countermeasures to, 269-271, 279-284, 289-293
aircraft flying formation, 270
Carpet, 279-282, 289-292
Chaff, 282-284, 292-293
corner reflectors, 459
effectiveness, 458
evasive action, 270
Radiation Laboratory
antijamming research and development, 249-260
Squirrel-Cage magnetron, 39-41
Radiation patterns of antennas
see Antennas, radiation patterns
Radio altimeters
AN/ARN-1; 196-197
f-m, 413
German, 140, 196-197, 454-455
vulnerability to jamming, 140, 196-197, 413
Radio Corporation of America
antennas and power transmission for nonradar countermeasures, 54-65
broad-band matching transformers, 134
ground-wave propagation, 127
jamming and antijamming techniques, 188-200
jamming transmitters, 160-187
noise jamming sources, 19-38
nonradar receiving and direction-finding techniques, 149-159
photomultiplier tube, 20-21
vacuum tube development, 39-53
Radio countermeasures, history of operational use
see History of operational use
Radio countermeasures, personnel training
see Personnel training
Radio countermeasures, summary of volume, 1-5
Radio countermeasures, test methods and equipment
see Test methods and equipment
Radio direction finders
see Direction finders
Radio Research Laboratory
antennas and power transmission for radar countermeasures, 54-65
antijamming research and development, 249-260
noise jamming sources, 19-38
portable spectrum analyzer, 73-74
radar deception, 230-248
radar jamming transmitters, 214-229
radar receiving and direction-finding equipment, 203-213
radio countermeasures, test methods and equipment, 66-75
Squirrel-Cage magnetrons, 39-41
theoretical studies of jamming, 80-146
vacuum tube development, 39-53
video spectrum analyzer, 30
Radio telegraphy jamming
c-w telegraphy, 396
effect on operators, 190
effectiveness, 393, 395, 397
tests, 399-400
types of interference, 190
Radio waveform for communications jamming modulation, 162-163
Radio waves, radiation and propagation, 123-131
analysis of ship echoes, 128-129
antenna studies, 123-127
ground-wave field intensity, 127
propagation studies, 127-128
radar reflections, 130-131
recommendations, 128
Radio-controlled devices, countermeasures to
see Guided missiles, countermeasures to
Radio-frequency power indicator, 418
Radio-frequency sweep generator, 414
Radio-frequency voltage regulator, 454
Radio-navigation aids
countermeasures to, 151, 413
types, 264
Radio-printing systems, 197-200
antijamming characteristics, 399
impulse and time code systems, 198
teleprinters, 197
Radio-printing systems, antijamming attachment, 198-200
basic method, 198-199
details of printer, 199-200
effectiveness, 199
printer signal, 198-199
recommendations, 200
Tuning Fork, 199-200
Railing type modulation
see Pulses, efficiency for jamming
Random jamming, 255-256
Random-pulsed triode cavity oscillator, 428
RC (resistance-capacitance) video filter for antijamming, 259
RCA
see Radio Corporation of America
RCM (radio countermeasures), history of operational use
see History of operational use
RCM (radio countermeasures), personnel training
see Personnel training
RCM (radio countermeasures), test methods and equipment
see Test methods and equipment
Receivers, 371-381
autodyne for spot jamming, 288
Bagful (recording receiver), 278-279, 287, 299
controlled-device, 380-381

direction-finding, 11, 210-212, 375-380, 457
early-warning, 11, 205-206, 375, 413
50 to 1000 mc, 454
for spot jamming, 177-178, 288
homing, 206-207, 295, 376-377, 379-380
monitoring, 10-11
panoramic, 153-155, 204-205, 371
scanning, 178
search, 136-139, 203-205, 208-213, 371-374
Receivers, jamming vulnerability, 166, 400-403
AN/ARC-4; 193
AN/SRW-2; 195
AN/SWR-2; 402-403
ARB, 402
BA-348-R, 193
BC-312-N, 193, 401-402
BC-342-N, 193, 401-402
BC-348-R, 401-402
BC-603-D, 193-194, 400
BC-624-A, 193, 400-401
BC-625-A, 401
BC-639-A, 193, 401
BC-652-A, 193, 401-402
BC-654-A, 193, 401
BC-659-A, 401-402
BC-659-B, 400
BC-669-C, 193, 401-402
BC-1000-A, 401
recommendations, 195
SCR-300-A, 193-194
SCR-511-B, 402
SCR-609-A, 193-194
Recommendations for future research
antijamming printing attachment, 200
communications ferrets, 150
jammer alignment systems, 179
multianode magnetrons, 50
photomultiplier tube, 21
radar antijamming modifications, 262-263
radio wave propagation, 128
receiver vulnerability, 195
scanning receivers, 178
split-anode magnetron, 43
Recording receiver (Bagful), 278-279, 287, 299
Rectification of noise, 88-90
effect on output spectra, 450
linear rectifier, 89
modulated signal in noise, 91-92
quadratic rectifiers, 90
Reflectors
see Corner reflectors; Window (radar confusion reflectors)
Resistance-capacitance video filter for antijamming, 259
Resnatrons, 51-53
characteristics, 51
design features, 51-52
860 mc tetrode, 52
high-power oscillator-amplifiers, 422
sealed-off type, 52-53
tunable tetrode, 52
X-124 and X-139 beam tetrodes, 428-429
Resonant systems, parameters, 427
Resonant systems, transmission lines
analysis, 132
mode separation in an oscillator, 133
resonant-line sections, 132, 446
RF-9/UPT oscillator for practice jammers, 421
R-f power indicator, 418
R-f sweep generator, 414
R-f voltage regulator, 454
RG-21/AU coaxial cable, 446
RHB (radar homing bomb), jamming susceptibility, 257, 404
Ridge wave guides, 132, 448
Ring transmitter (radar operator training aid), 79
RL (Radiation Laboratory)
antijamming research and development, 249-260
Squirrel-Cage magnetron, 39-41
RLC filter for antijamming, 252
Rope (electromagnetic-wave reflector), 113-115, 237-240, 363-365
balloon-supported, 411
dispensers, 239-240, 364-365
field tests, 411
operation, 344
production of vertically polarized radar echoes, 410
response characteristics, 240, 363
ribbon-shaped, 113
Tinsel (Fishline), 238
tuned, 115, 230-231, 237-238
types, 232
untuned, 230-231, 239-240
use against EW radar, 359
RP-347 spectrum analyzer, 69-70, 416
RP-392 K spectrum analyzer, 417
RRL
see Radio Research Laboratory
Ruffian (German bomber navigational aid), 264
Rug (radar jammer), 384-385
advantages, 384
effectiveness, 304
modifications for spot jamming, 457
use against SLC radar, 361-362

S-27D hallicrafter search receiver, 371
Sawtooth frequency modulation, 106-107
S-band antennas, 441
SC radar, use in antijamming training, 422
Scanning receivers, 178
SCR-268 radar
antijamming modifications, 259
detector video replacement units, 405
jamming tests, 403
susceptibility to jamming, 257
SCR-296 radar, antijamming modifications, 259
SCR-300-A receiver, vulnerability to jamming, 193-194
SCR-511-B receiver, jamming vulnerability, 402
SCR-521A radar, antijamming characteristics, 403
SCR-522A search receiver, 371
SCR-536 portable radiophone, operating characteristics, 402
SCR-545 radar, susceptibility to jamming, 257, 404
SCR-591 spot jammer, 176-177
SCR-609-A receiver, vulnerability to jamming, 193-194
SCR-617 radar, antijamming characteristics, 403
SCR-717B radar, antijamming characteristics, 259-260, 403, 406
SCR-720A radar, jamming susceptibility, 404
SD-849 Squirrel-Cage magnetron, 426
Search jammers, automatic, 181-182
Beagle, 182
Broom, 181-182, 393
Search receivers, 9-11, 371-374
antennas, 55, 126-127, 438, 440
antijamming measures for, 408
Bagful, 278-279, 287, 299
Blinker, 287-288
communications, 371
design, 455-456
for proximity fuze countermeasure, 159
jamming vulnerability, 193, 401
microwave, 288, 420
panoramic, 153-155, 204-205, 371
pulsed, 371
radar, 203-205, 208-213, 371-374
range, 10
requirements, 150
suppression of spurious response, 150
test transmitter, 414
tuning units, 372-373
Search receivers, theoretical studies, 136-139
comparison with experimental results, 139
ignoramus theory, 138-139
monochromatic case, 137
uncorrelated model, 137-139

Searchlight-control radar, countermeasures to
see SLC radar (searchlight-control), countermeasures to
Searchlight-control warning receiver, 11
Setter (airborne direction-finding attachment), 375-376
Shell-burst echoes, 245
Ship echoes
air-and sea-zone, 128
operational considerations, 129
parameters and formulas, 128-129
Ship-borne antennas
bandwidth, 55
directivity, 55-56
installation, 57
method of obtaining patterns, 443
models, 143, 442
wave antenna, 64
Ship-borne direction finder, 378, 379
Ship-borne jammers, 185-187, 390-393
AN/SRQ-1; 186-187, 392
AN/SRQ-11; 183, 185
Elephant, 228-229, 253-254, 300, 390-391
MAS, 185-186, 392-393
Model Tea, 64
power requirements, 460
Signal generators
see Oscillators
Signal visibility through noise, 91-99
condition for visibility on oscilloscope screen, 98
deflection modulation, 98-99
effects of integration, 96-99
intensity modulation, 98-99
reception of radar signals, 93-96
rectification of a modulated signal, 91-92
Signal-repeating systems
broad-band, 455
Peter Pan, 155-159, 381
Piano, 182-183
Silent Knight (blanking receiver circuit), 373
6D4 gas triode, 449-451
clipping of noise output, 102, 450
housing and magnet for noise source, 23-25, 423, 450
noise output, 449
tube tester, 31
use as noise source, 450-451
6J21 tunable magnetron, 425, 428
612 L multianode magnetron, 44
Skirted stub antenna, 435
SLC radar (searchlight-control), countermeasures to, 360-365
Dina, 361-362
jamming, 12
jamming susceptibility, 257, 404
operational problems, 352, 360-361
Porcupines, 362-363
Rope, 363-365
Rug, 361-362
SLC (searchlight-control) warning receiver, 11
Sleeve antennas, 65
advantages, 443
AS-181/APT, 435-436
construction, 445
impedance characteristics, 443
radiation patterns, 443
Slot antennas, 436-437
modeling for pattern measurements, 442
wide-band, 444
Sound analyzers
General Radio, 30-31
range extender, 451
Spark jammers, 171-172
expendable, 392
theoretical efficiency, 382
Specifications
Chaff, 231, 408, 410
guided missiles, jammers, 180
magnetrons, 44-45
noise sources for jamming, 19
Spectral distribution of clipped noise, 81, 84-87, 102
Spectrum analyzers, 68-74, 415-417
10-3500 mc, 70-71
100-1400 mc, 68-70
audio, 30-31
crystal mixers, 416
double superheterodyne type, 416
for carrier frequencies, 416
impedance bridge, 115-mc, 72
low-frequency, 416
narrow-band amplifier, 115-mc, 71
OCC, 68-70
panoramic, 415
pulse analyzer, 414, 417
RP-347; 69-70, 416
RP-392 K, 417
studies on crystals, 72
summary of development work, 423-424
sweeping local oscillator type, 71-73
variable input impedance, 72
video, 30, 416
wide - band intermediate - frequency, 73-74
Speech-masking effectiveness of jamming, 393
Speed-X buzzer (noise generator), 28
Spinners, antenna, 377-378
Spinning loop aircraft direction finder, 380
Split can antenna, 436, 439
Split-anode magnetrons
see Magnetrons, split-anode
Spoofs, naval (seaborne corner reflectors), 459-460
Spot jammers, 176-179
airborne multiple jammer, 178, 397
AN/ARQ-10 (SCR-591); 176-177
Carpet, 275, 280, 385, 457
Cigar, 389
design considerations, 216
evaluation, 168, 276
MAS, 392
Rug, 457
Spot jamming techniques, 176-179
alignment systems, 178-179, 397
broad-band scanning technique, 178
comparison with barrage jamming, 168, 216
continuous wave modulation, 164-165
frequency modulation, 387
frequency setting, 169, 219-221, 278-279, 393
listening-through system, 177-178
narrow-band receiver technique, 178
operational use, 345-346
operator training, 79, 276
receivers, 177-178, 288
requirements, 176-177, 460
selection of type, 168, 216, 221
Spud (radar search receiver), 373
Squirrel-Cage magnetrons, 39-41, 426-428
Stardust (pulse repeater), 412
Static burst jamming, 397
Steel antenna, advantages, 443
Step-tone jammer, effectiveness, 401
Stingaree antennas, 445
Stopwatch (automatic jammer alignment system)
design, 394
recommendations for future research, 179
Stub antennas
radiation patterns, 441
skirted stub, 435
thick stub, 433-434
with series matching sections, 443
Submarine direction-finding system, 379
Superheterodyne spectrum analyzer, 416
Sweep generator, wide-band r-f, 414
SX-25 (communications receiver), use as noise analyzer, 420
Sylvania Electric Products
Squirrel-Cage magnetron, 39-41
vacuum tube development, 39-53

Tail (homing attachment for direction finders), 376
Tank antennas, 433

Tape recorders, magnetic, 155-158
AN/ARQ-12; 156-158, 380-381
AN/SRQ-2; 156-158, 380-381
use in Peter Pan jamming system, 155-157, 381
Targets, frequency sensitivity, 122-123
TDY radar jamming transmitter, 214
TDY rotating antenna, effectiveness, 342
Teflon as insulator, 37
Telegraphy jamming
c-w telegraphy, 396
effect on operators, 190
effectiveness, 393, 395, 397
teleprinters, 197
teletype, 194, 401
tests, 399-400
types of interference, 190
Test methods and equipment, 66-77, 413-422
Carpet checker, 418
Carpet output indicator, 418
communications receiver vulnerability to jamming, 66-68
crystal probes, 76
crystal rectifier voltmeter, 420
double-peaking amplifier-alignment unit, 76
frequency meters, 76, 78, 417-418
high-frequency calorimetric wattmeter, 75, 418-419
noise analyzer, 420
noise tube tester, 419-420
r-f power measurement, 418-419
signal generators, 67-68, 413-415, 420-422, 425-429
spectrum analyzers, 30-31, 68-74, 415-417, 424
summary of types and applications, 77-79
test oscillators, 76, 420
transmitter output indicator, 418
u-h-f power meter, 418
Thermal noise, jamming effectiveness, 163-164
Thermistor bridge, self-calibrating, 419
Time and impulse code systems
Beechnut, 198, 399
Voflag, 198, 399
Tinsel (modulation method), 172
Tinsel Rope (radar deception device), 238
TPQ-T2 antijamming training set, 261-262, 421
Trailing-wire antennas, 64-65, 443
Training methods and equipment
see Personnel training
Transformer design
Bazooka, 433
broad-band wave guide-to-line junction, 134
cores, 33, 36-37
eddy-current loss, 454
for noise jamming, 102-104
for 100 to 3000 mc, 453-454
for radio power supplies, 453
ideal load, 133
performance of matching sections, 133
series of quarter- and half-wave sections, 134
skin depth, 102-104
synthesis of matching sections, 134
video, 32-38, 454
wide-band balancing transformer, 134
Transformers, noise
see Video noise transformers
Transmission lines, applications, 131-135
antennas, 58
design of matching transformers, 133-134
filters, 134-135
properties, 131-132
radar countermeasures, 63
resonant circuits and systems, 132-133
velocity of propagation in coaxial line, 132
Transmitter for checking operation of search receiver, 414
Transmitter output indicator, 418
Transmitters, jamming
see Jammers
TS-53/AP Carpet checker, 418
TS-54/AP spectrum analyzer
graphical representation of functioning, 73-74
power output of video amplifier, 74
resolving power, 73-74
TS-92/AP bandwidth adjustment indicator, 417
TS-99/AP heterodyne frequency meter, 417
TS-109/SPA interference generator, 79, 261-262, 420-421
TS-118/AP radio-frequency power indicator, 418
Tuba (ground-based jammer), 390-391
countermeasure to AI radar, 140
operational use, 300-302
Tube development
see Electron tube development
Tube tester, noise, 31
Tubes, gas
see Gas tube noise sources for jamming
Tungar bulbs, use as noise generators, 452
Tuning units for radar search receivers, 372-373
Turnstiles (confusion reflector), 230-231, 238-239
2C4 gas triode, noise output, 449
2D21 gas tetrode, noise output, 450
2K28 u-h-f oscillator, 429
2K48 local oscillator tube, 40-41
2K49 local oscillator tube, 40-41
233A airborne transceiver, jamming vulnerability, 401
2050 gas tube for noise jamming, 450

U 400 tube tester, 31
U-1500 pulser (signal generator), 414-415
U-h-f (ultra-high-frequency) antennas, 444
U-h-f (ultra-high-frequency) filters
design equations and performance curves, 452
mechanical design, 453
U-h-f (ultra-high-frequency) oscillators
see Oscillators, ultra-high-frequency
U-h-f (ultra-high-frequency) power meter, 418
U-h-f (ultra-high-frequency) resonant systems, parameters, 427
University of California, resnatron, 51

Vacuum tube development
see Electron tube development
V-antennas, 64
Velocity-modulation tube, magnetically-focused, 426
V-h-f (very-high-frequency) homing systems, 377
V-h-f (very-high-frequency) radar screen, 295
Vicalloy recording tape, 157
Video amplifiers for antijamming, 406
Video analyzer, radar, 391
Video filter for antijamming, 259, 405
Video noise generators
constriction oscillator, 25, 451
6D4 noise unit, 23-25
Video noise transformers, 32-38
core losses, 34
core materials, 33
design, 36-38, 454
impedance measurements, 33
tests, 37-38
Video spectrum analyzer, 30, 416
Visual detection of radar signals
evaluation, 431-432
sensitivity, 95
signal-to-noise ratio, 93-94
Voflag (code system), 198, 399
Voice substitute systems, 197-200
antijamming characteristics, 198-200, 399
impulse and time code systems, 198
teleprinters, 197
Voice-frequency noise generator, 451
Voltage regulator, r-f, 454

[redacted]

Voltmeter, crystal rectifier, 420
Voltmeter, noise-measuring, 31, 451

Walkie-talkies, jammer for, 382
Warning receivers, 205-206
  Boozer, 206, 287, 299
  circuits, 213
  gun-laying radar, 11
  purpose, 11
  searchlight control, 11
  test buzzer, 414
  time element, 206
  Zero Catch II; 375
Wattmeter, high-frequency calorimetric, 418-419
  coaxial line sections, 75
  microwave, 419
  water-load type, 419
Wattmeter, waveguide, 448
Wave analyzer, 30-31
Wave antennas
  Beverage wave antenna, 64
  comparison with vertical radiators, 444
  measurements over sandy soil, 444
Wave guides
  antennas, 434
  directional pickup and wattmeter for guides, 448
  dummy antenna, 448
  installation, 447
  moisture in guides, 447, 448
  properties, 131-132
  ridge guides, 132, 448
  use of resonant probe, 447
  wide-band mixers, 447
Waveguide output magnetrons, 425
Wavemeter, 417-418
Westinghouse Research Laboratories, vacuum-tube development, 39-53, 427
Whip antennas, 440-441
Window (radar confusion reflectors), 110-123, 230-245, 408-412
  Angels, 116-117, 230-231, 241-243, 411-412
  Birdnesting phenomena, 231
  Chaff, 111-113, 232-237, 273-275, 408-410
  countermeasures to, 117-122, 253-254
  field tests, 412
  operation, 13
  pulse length, 117
  Rope, 113-115, 237-240, 363-365, 410
  squares or sheets, 244
  tuned and untuned, 230-231
  Turnstiles, 230-231, 238-239
  types, 230-231
  use in bombs, 409
Wing antennas, 65
Wurzburg (German radar)
  antijamming devices, 457
  frequency range, 234
Wurzburg simulator, 406-407

X-124 and X-139 resnatrons, 428-429
XA-2 airborne jammer for radar, 228
X-band jammers
  test jammer, 415
  use of A-131 magnetron, 425
XN-1 magnetic tape recorder, 156-158

Z-668 reflex klystron, 71
Zero Catch II (early-warning radar receiver), 375
ZP-522 c-w oscillator, 428
ZP-572 lighthouse triode, 41
ZP-579 split-anode magnetron
  characteristics, 40, 43
  design and performance, 422
  efficiency, 423
ZP-584 split-anode magnetron, 40, 43
ZP-590 split-anode magnetron
  characteristics, 40
  electron escape, 42
  frequency range, 43, 45
ZP-594 multianode magnetron, 424
  cathode, 49
  characteristics, 44
ZP-595 split-anode magnetron, 50-51
  characteristics, 51
  construction, 422
  modification, 51
ZP-597 multianode magnetron
  cathode, 49
  characteristics, 44
  noise modulation, 427
  parasitic resonance, 424
ZP-599 split-anode magnetron, 44, 45
ZP-612 multianode magnetron, 46-50
  cathode, 48
  characteristics, 44
  response to noise modulation, 428
  tuning method, 47-48
  wave-guide transformer, 46, 49
ZP-615 multianode magnetron
  cathode, 49
  characteristics, 44
  tuning structure, 49
ZP-616 multianode magnetron, 424
  characteristics, 44
  construction, 49
  tuning method, 48
ZP-633 split-anode magnetron, 40, 43, 423
ZP-636 split-anode magnetron
  characteristics, 51
  construction, 50
  design, 423
ZP-639 multianode magnetron, 44, 49
ZP-646 split-anode magnetron
  characteristics, 40, 43
  electron escape, 42
ZP-647 neutrode magnetron, 43-45
  characteristics, 44
  frequency range, 45
ZP-652 magnetron, 40, 424
ZP-666 split-anode magnetron, 40, 43
ZP-675 neutrode magnetron, 40, 43
ZP-676 neutrode magnetron, 40, 43, 45
ZP-677 neutrode magnetron, 43
ZP-685 neutrode magnetron, 43-45
ZP-693 multianode magnetron, 44
ZP-838 multianode magnetron, 44

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